APPLIED SEDIMENTATION

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APPLIED SEDIMENTATION

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PREFACE

This symposium considers the practical applications of sedimentation. It is designed (1) to describe aspects of mutual interest to the geologist and to the engineer so that each can understand the other's problems and thus cooperate more effectively in their work; (2) provide information for the consulting geologist who may not be completely familiar with specific problems; and (3) acquaint students with the many practical applications of sedimentation so that they may be more fully informed as to possibilities for a career in this field. Each chapter is a summary of a comprehensive subject. Bibliographies are given for benefit of readers who may wish to pursue topics further. Key articles are characterized by an asterisk in the lists of references.

The work has been prepared under the sponsorship of the Committee on Symposium on Sedimentation of the Division of Geology and Geography of the National Research Council. The Committee wishes to express its appreciation to Dr. Arthur Bevan, Chairman of the Division, and to Miss M. L. Johnson, Secretary of the Division, for their help in the preparation of the symposium; and to Mr. G. D. Meid, Business Manager of the National Academy of Sciences, and Dr. David M. Delo, Executive Secretary of the Division, for aid in arranging publication. Special credit is due Dr. Arthur B. Cleaves, Professor of Engineering Geology, Washington University, St. Louis, Missouri, for assistance in organizing chapters on engineering topics in Part 2 of the symposium. Acknowledgment is also due the University of Wisconsin Alumni Research Foundation for a grant that helped me in early work on the symposium.

The practical applications of sedimentation are so large in number and so complicated in scope that the Committee felt that it would accomplish more good by inviting a group of specialists to write chapters in their own field of interest rather than by trying to prepare a handbook itself, a handbook which in places would be only a compilation. As it has not been practicable to procure articles in all fields, the coverage of the subject is not complete. A sufficient number of articles, however, is included to indicate the general usefulness of sedimentation in practical endeavor.

The geologist is constantly called upon to indicate the character of sediments at some place beneath the surface of the earth where he cannot see them either in outcrop or in samples from drill holes. He has to predict what they will be like by means of interpreting what he has seen at some other place. He is well aware of the variability of sediments, and on the basis of his past experience and his knowledge of the mode of origin of sediments he is the person best qualified to make predictions. A knowledge of the basic principles of sedimentation and stratigraphy is essential for this purpose. The geologist, however, also must understand the things the engineer wishes to do with the sediment; and the engineer should understand the general geologic problems involved and the limitations of geologic work, so that he can utilize the services of the geologist intelligently. The engineer above all should be conscious of the variability of sediments. It is hoped that this symposium will help accomplish these purposes.

Three types of earth materials are considered in this symposium: (1) recent or slightly consolidated sediments; (2) ancient or maturely consolidated sediments, that is, sedimentary rocks formed in the geologic past; and (3) residual soils, or soils weathered in place. Soil technically perhaps is not a sediment, but as it has many of the characteristics of soft sediments, particularly with respect to its effect upon engineering problems, it is considered here.

A sediment is an aggregate of solid particles that have been moved from one or more places of origin to some place of rest. Its properties depend on (1) the chemical, physical, and biologic nature of the solid constituents, (2) the character of the material that fills the pore spaces, and (3) the changes that take place in the sediment with time, due either to applied stress or to chemical reactions. The practical applications of sedimentation therefore involve both the nature of the sediment and the processes that affect them.

The symposium contains thirty-five articles grouped under seven topics: (1) basic principles of sedimentation, (2) engineering problems involving strength of sediments, (3) applications of processes of sedimentation, (4) applications involving nature of constituents, (5) economic mineral deposits, (6) petroleum geology problems, and (7) military applications.

The first topic on principles is essential for the proper understanding of the economic applications of sedimentation. The second and third topics, relating respectively to strength of sediments and the processes of sedimentation, are of special interest to engineers. The engineer must have adequate foundations for his structures. Frequently he is called upon to build roads, airports, dams, tunnels, or buildings in areas of relatively soft rocks, where he has little choice as to location. He therefore must do the best he can with what foundation material he has, and he is vitally concerned about the strength of the sediments or their ability to support the designed load.

The processes of sedimentation, especially processes relating to the transport of constituent particles of sediments, have tremendous impact upon our national economy. Millions of dollars each year are lost by floods, beach erosion, shoaling of harbors, silting of reservoirs and canals, soil erosion, and landslides. Engineers and geologists are constantly called upon to cope with these problems.

The nature of the sediments, discussed in Part 4, also interests the engineer. This topic includes chapters on aggregate for concrete, sand for foundry molds, and clay minerals. The last topic is of particular concern to the geologist as well as to the engineer, because of the materially different properties of the various clay minerals and the different effects of base exchange upon clay.

However, the economic utilization of the constituent materials of sediments lies mainly outside the field of engineering. Both the mining and petroleum industries depend on the products of sedimentation for their livelihood. As McKelvey shows in this symposium, the total value of economic mineral materials, exclusive of coal and oil, obtained annually from sediments in the United States is almost one billion dollars. A great many kinds of raw mineral materials are used commercially, but space permits the discussion of only a few token examples in this symposium. These chapters, presented in Part 5, should indicate to mining geologists the usefulness of knowledge of sedimentation in their work.

More than 6,000 geologists are directly or indirectly engaged in the search for petroleum, which is found almost exclusively in sedimentary rocks. In their training and in their professional work, geologists thus become familiar with the applications of sedimentation to petroleum geology. Rather than duplicate material of more or less common knowledge to geologists, the Committee feels that it is preferable to emphasize the less well-known applications of sedimentation and to restrict chapters on petroleum geology (in Part 6) to a few topics of current interest.

Geology is of material assistance to the Army and the Navy during time of war. Many of the geologic problems deal with sedimentation. Two chapters on this subject are presented in Part 7. The usefulness of sedimentation, however, is greater than these chapters indicate, as work of a confidential nature is not included.

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San Francisco, California
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PART 1

BASIC PRINCIPLES OF SEDIMENTATION

Chapter 1

DYNAMICS OF SEDIMENTATION *

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Geologists and engineers need to understand sediments. They should know what they are like, why they are the way they are, and what factors cause them to change. The object of this paper is to summarize the principal features of sediments, emphasizing the processes that lead to their formation or that cause them to change once they have been formed. As sediments are largely a product of the environment in which they are formed, special attention is given to environments of deposition. This chapter, like all other chapters in this symposium, is a condensation of a complicated subject. A list of 100 references is included for benefit of persons desiring further information on particular topics.

Sediments are aggregates of particles that come to rest in some place after having been transported laterally or vertically for some distance. When first deposited, the particles are unconsolidated or essentially unconsolidated. The geologist calls such deposits *recent sediments*. With time the sediments consolidate and harden into rock. Such consolidated sediments are called *ancient sediments*. During this process, cementing material is deposited in the pore spaces; new minerals form or old minerals grow, thus binding particles to one another; and pressure of overburden compresses the sediment, causing the constituent particles to interlock with one another. When rocks weather in place they are altered physically and chemically and eventually are transformed into soil. As soils or weathered rocks have many of the properties of recent or unconsolidated sediments, it is convenient to consider them in connection with sediments. Technically they could be called

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sediments, because their constituents have settled under the influence of gravity, albeit only a very small distance. For more detailed accounts of sedimentation see the works of Gilbert (1890), Walther (1894), Grabau (1913), Twenhofel (1932, 1939), Boswell (1933), Hatch, Rastall, and Black (1938), Trask (1939), Shrock (1948), and Pettijohn (1949).

Sedimentation consists of five fundamental processes: (1) weathering, (2) erosion, (3) transportation, (4) deposition, and (5) diagenesis or consolidation into rock.

WEATHERING

Most of the constituent particles of sediments are derived from rocks or earth materials that have been more or less weathered. The original constituents of sediments, of course, can come from unweathered rock, but weathering and concomitant solution are the dominant processes by which rock or soil constituents are transformed into a state whereby they can be eroded and transported to some place of deposition. Weathering is essentially a process of soil formation; for details the reader should consult standard references on the subject such as: Baver (1948), Clarke (1924), Goldich (1938), Goldschmidt (1937), Jenny (1941), Leith and Mead (1915), Polynov (1937), or Reiche (1945).

Weathering consists of two fundamental processes: (1) mechanical disintegration and (2) chemical solution. Living organisms, particularly microorganisms, also play an important role, but in the last analysis organic action is essentially a question of physical disruption or chemical solution of rock and earth constituents.

Five fundamental factors, as Jenny has pointed out, influence weathering: (1) parent rock material; (2) climate, particularly the temperature and rainfall; (3) physical environment in which the weathering takes place, especially topography or shape of the land surface; (4) length of time the processes operate; and (5) action of organisms. To this might possibly be added a sixth factor—the dynamics of the environment, that is, the ratio of the rate of weathering to rate of removal of weathered particles by erosion. If erosion is rapid, soil-forming processes cannot proceed very far toward maturity before the constituents are removed. Moreover, these principal variables that affect weathering and soils to a considerable extent are mutually interrelated.

Mechanical weathering is largely a question of thermal expansion and strength of the mineral constituents. Mechanical disintegration is dominant in arid areas and in cold regions; chemical weathering prevails in humid, tropic areas. Steep slopes facilitate mechanical erosion; flat areas favor accumulation of water in the rocks and soil and thus help chemical weathering.

Chemical weathering is essentially a question of exchange and movement of ions. Base (cation) exchange is a dominant process. Critical factors are (1) concentration of ions, particularly hydrogen, sodium, calcium, and magnesium; (2) oxidation-reduction potential; and (3) temperature. Basic rocks, that is, rocks rich in calcium and magnesium and relatively low in silica, tend to be more susceptible to chemical weathering than acid rocks, which are rich in silica and alkalies, but, because the hydrogen-ion concentration of the soil is an important factor, this generalization is subject to exceptions. Many sedimentary rocks weather more rapidly than igneous rocks because of their greater permeability. Moisture and temperature affect the growth of microorganisms, which in turn influence chemical weathering. The longer the time that climate, topography, and organic activity remain essentially unchanged for given conditions of runoff, the more thoroughly the rocks are weathered into soil.

When weathering has proceeded to the state where soil has formed, the earth materials are divided into four distinct zones from the surface downward: (1) an upper leached zone relatively rich in organic matter, the *A* zone; (2) an underlying zone in which some of the materials transported or leached from the upper zone have been deposited, the *B* zone; (3) a still lower zone of partially weathered rock, the *C* zone; and (4) essentially unweathered rock.

If weathering proceeds for a long time, the soil approaches maturity, which results in the formation of clay minerals typical of the environment and in the production of many fine particles. The constituents of such soils, when transported to a place of deposition, form a sediment having a far different reaction to imposed loads than sediments whose constituents are derived from areas in which the rocks have not developed a chemically mature soil. Students of soil mechanics might well consider this point in interpreting the strength of foundation materials.

EROSION

Both mechanical and chemical processes cause erosion. Because of the close relationship between erosion, transportation, and deposition, it is convenient to discuss the mechanical aspects of these subjects in sequence and then take up chemical weathering and solution.

Mechanical erosion consists of two processes: (1) plucking or forcing particles from their position of rest, and (2) abrading rocks by impact of moving particles. The size of the particle, the velocity of the transporting agent, and the cohesiveness of the rock or soil are factors in the plucking action. Alternate freezing and thawing and the growth of plants in cracks are agents in the forcing apart of rocks. The size, quantity, hardness, and velocity of the moving particles and of the object that is struck are factors in the abrading action.

Water is the chief mechanical agent of erosion, but wind, ice, gravity, volcanic explosions, plants, and animals also act. Water acts in at least three different ways: (1) when running off the surface of the land before it collects in streams; (2) in streams; and (3) in bodies of essentially standing water, namely lakes and the ocean. Erosion is intimately associated with the ability of the water to transport material. If the water is fully loaded and is transporting all the material of a given size it can transport, relatively few particles of that size can be picked up; or, to be more precise, the net erosion of such particles is small. However, when the water is underloaded, erosion is effective. The erosive power, that is, the ability of water to pick up particles, depends upon the energy relationships of the moving water, particularly the turbulence. Turbulence is discussed in the next section.

Water moving over relatively steep surfaces of land before it reaches streams acts in some ways as a thin, flat sheet (Paige, 1912). The thickness and continuity of the sheet depend upon the average slope of the land, the amount of rain that has fallen, the rate of infiltration of water into the soil, and the interference of grass, plants, and other obstacles with its free movement. If the obstacles to downward flow of the water are numerous, relatively little material is eroded, as, for example, in humid regions where plants are plentiful or in areas of highly pervious soil which absorbs the water readily. Sheet erosion is best developed in arid or semi-arid regions, and it results in a topography that comprises relatively steep slopes above and more gentle slopes below, where the water spreads out over a fan-shaped area before collecting in a stream or some body of standing water. In humid areas the fan-shaped areas usually are less well developed.

The steep slopes above seem to be related to the rate of weathering of the rocks and the permeability of the soil. The flatter slopes below represent an equilibrium profile determined by the average load of sediment that the water is carrying. If the water is underloaded it will cut; if overloaded it will deposit. The same fundamental principles of transport and erosion apply to this water moving in a sheet as to water flowing in streams or in the ocean, but the generally shallow depth with respect to width results in a different profile of erosion.

The principal erosive effect in streams is scour of the banks and the bottom. Erosion in the sea and in lakes is due principally to waves and currents, and to a minor extent to chemical solution. The abrasion of rocks along the shore or on the bottom in shallow water is caused chiefly by the impact of sand and rock particles carried by moving water. Loose or slightly consolidated sediment may be scoured by wave action or by ocean currents.

Wind erosion is similar to water erosion. All kinds of earth materials are worn away by impact of particles blown against them by the wind. Constituent particles of loosely consolidated sediments are also plucked as wind blows over them, provided that the wind is strong enough and the sediments are sufficiently dry (Bagnold, 1941).

Ice flows plastically, much like a viscous body of tar. The essential factors affecting its movement are: the mass of ice; the gradient, particularly the surface configuration over which it flows; and the distribution of temperature throughout the ice (Thwaites, 1941). The rate of movement of ice and hence the rate of erosion are accelerated by increased gradient of land and addition of snow to the upper parts of the mass of moving ice. As the plasticity of most solids increases with increase in temperature, it could be argued that ice would flow faster if its average temperature was relatively near the freezing point of water.

Ice acts as an agent of erosion in the following ways: Rock fragments frozen in the ice abrade the rock or soil over which the ice flows. Ice plucks rock fragments as it passes over them. It also pushes masses of rock and earth ahead of it as it moves. Rocks are disrupted by alternate expansion and contraction as the temperature of the ice varies or as the ice melts and refreezes in cracks or crevices. Ice is reported (Blackwelder, 1940) to increase materially in hardness as the temperature decreases, and therefore ice alone, without the aid of rock fragments, can scour soft sediments and rocks.

Volcanic explosions can disrupt rock fragments as the explosive gases and masses of lava and rock are forced upward by the explosion, but the erosion of material in this way is of minor import, as active volcanoes are relatively few in number.

Where slopes are steep or smooth, gravity can be an agent of erosion; but generally it is only a secondary agent, because the stability of the rock fragments must first be upset by some other agency so that fragments can become unbalanced and thus slide or roll down the slope.

Living matter is an important factor in erosion, but its principal effect is indirect, because the living material influences the erosive action of some other agent. Roots, however, are direct agents of erosion when they grow in cracks and force a part of the rock to fall away. The most profound effect of living material, however, is the action of vegetation in inhibiting the flow of rainwash. Man, because of his various uses of land and the resulting increase in soil erosion, is also an indirect agent. (See Chapters 22 and 23.)

TRANSPORTATION

The same six agents of erosion, namely, water, wind, ice, volcanic explosions, gravity, and biologic activity, also control transportation but in a varying degree. With water, the principal factors that affect transport are: turbulence; ratio of settling velocity to lateral motion of water (currents); shape, size, density, and quantity of particles; and movement along the bottom by saltation (jumping), rolling, or undermining. (Rubey, 1938; R. D. Russell, 1939; Rittenhouse, 1944).

Turbulence is non-linear motion of masses of water as the water moves. (See Chapter 3.) Turbulence is characterized by vertical and horizontal eddies which tend to keep particles in suspension. The principal factors that affect transport by turbulence are the quantity, velocity, and temperature of the water that is moving, the load, and the shape or roughness of the surface over which the body of water moves. Thus gradient of stream bed, volume of water, and presence of objects that impede flow are major factors. The quantity and shape of material already in suspension also influence the amount of additional material that can be transported, because turbulence is related to energy and a given discharge moving over a given slope can transport in suspension only a given amount of material of a given size.

Debris also is transported along the bottom of a stream. Turbulence may lift particles for a short distance above the bottom, but it may not be strong enough to maintain them in suspension. Consequently they fall to the bottom, only to be lifted again at a later time when turbulence once more reaches a sufficient magnitude. Thus particles jump or roll along the bed in pulses. This process is called saltation. In addition many particles are round and act like ball bearings, causing heavier rock fragments that rest upon them to glide downstream. This process is particularly noticeable in the alluvial fans of the desert.

In the sea or in a lake many detrital particles are carried a long distance after they enter the sea or lake. Even though turbulence may not be strong enough to maintain the particles in suspension, the mass of water in which the particles lie may move. The particles thus are transported laterally while they settle downward through the mass of moving water. Transportation of this type is a statistical phenomenon. For given size distribution of sediment and for given velocity and depth of water, the average size of particles that are transported decreases progressively with distance of transport, but the range in size of particles found in a mass of water under any given conditions varies about a mean grain size, and the average deviation in size of particle from that mean grain size varies according to the conditions of transport. The subject of transport in the sea is still not well understood, but it is of such vital importance that it is now being attacked actively by oceanographic institutions.

Transport of sediment by wind follows essentially the same laws as does transport by water, except that, because of its low density compared with water, air is a less effective agent of transport (Bagnold, 1941; Loess symposium, 1945). However, particles are also blown through the air or moved along the ground by the same principle of saltation that applies to water.

Ice transports material either within or on top of the ice or by shoving masses of earth and rock ahead of it as it moves. Transportation by volcanism is a question of the force of the explosion and the direction and strength of the prevailing wind. Fine ash can be carried many miles, as the Katmai explosion in Alaska indicated. The distance that objects will be transported under the influence of gravity is governed by the angle and smoothness of the slope along which the material moves, the coefficient of friction, and the amount (mass) of material that moves. Organisms are minor agents of transportation. Even man moves relatively little material compared with nature.

DEPOSITION

The most important factor in sedimentation is deposition. Once the sediments have accumulated in their final resting place, their general nature is fairly well formulated. Subsequent changes, for most sediments at least, alter their characteristics relatively little. The processes of deposition are complex and the products are manifold. The same six agents that affect erosion and transportation likewise control deposition.

WATER

The processes of deposition in water are essentially a question of energy, place, and time. If the energy available to move constituents that are in the act of being transported decreases, some of the particles can no longer be transported and they come to rest. The environment in which the particles are being transported profoundly affects the types of sediment that are deposited, primarily because of the effect of the configuration of the basin of deposition upon the movement of the transporting agent, be it water, air, or ice. Diastrophism, or movement of the crust of the earth, is a critical factor, for diastrophism not only influences the shape of the environment of deposition, but it also affects the configuration of the land which supplies the debris that is deposited. Time is a factor because the rate of movement of particles determines whether the particles will be picked up, moved, or deposited. Furthermore, sediments, once they have been deposited, change in the course of time (diagenesis).

The three factors—energy, place, and time—are intimately interrelated. The principal source of energy comes from streams, currents, wind, volcanic explosions, or from material that has acquired potential energy by having been placed in a higher position than it once was, by evaporation, convection, turbulence, or diastrophism. The effect of environment is treated in a later section. The influence of time, particularly the rate of change, is complicated. The principal effect of time, especially with respect to deposition by water, is the rate of change in velocity, ds/dt. To this also should be added the change in direction and the rate of change in direction. In other words, deposition is strongly influenced by turbulence when the interval of time is short and by changes in average velocity when the time is not short.

Turbulence affects the size of particle that is laid down, that is, the size distribution of the sediments (grading curve). If the average velocity of the water is fairly constant and fluctuations in turbulence are not too great, well-sorted sediments are deposited. Particles small enough to stay in suspension for a significant interval of time are transported away from the locus of deposition, and the particles that settle to the bottom are comparatively well graded in size. Consequently a relatively large proportion of the particles deviate in size slightly from the average particle deposited. The energy relations that govern transport are too complicated to discuss here, but, even though the average deviation in velocity of water is proportionately the same with respect to the average velocity of the water, the degree of sorting of the constituents (uniformity coefficient of the engineers) is not the same. Slowly moving water seemingly leads to poorer sorting than fast-moving water. Silts are rarely as well sorted as sands.

The size distribution of the constituent particles, because of its dependence upon the motion of the water in which the sediments accumulate, therefore is an index of the mode of deposition. If one process is operating, the size distribution is more likely to be symmetrical than if more than one process is operating. For example, if the locus of deposition receives debris from two or more sources the material deposited will have one or more size distributions deposited upon another, with the result that the size distribution of the sediments becomes skewed or has two or more modes. Likewise, if an area is subject to variations in average velocity, a similar result could arise. Also, as discussed below, sediments deposited upon submerged ridges commonly are disturbed or riled by moving currents, which cause the fine particles to be carried away and deposited elsewhere. The sediments on the ridges are relatively well sorted, but those deposited in the lee (if the word lee can be used with respect to moving water) are likely to be skewed because they receive the normal supply of detritus for that particular distance from land as well as debris winnowed away from the nearby ridge.

If the velocity of the water changes so that it moves at a different velocity or in a different direction for any appreciable length of time, or if the supply of debris changes in character, the resulting size distribution of the sediments is different. In this way laminae or strata are formed. The development of layers is one of the principal characteristics of sediments (Andrée, 1916; Barrell, 1917; Bucher, 1919; Antevs, 1922; Rubey, 1930; Weller, 1930; McKee, 1939; Payne, 1942; Alling, 1945).

Sediments ordinarily are deposited in nearly horizontal layers. However, if the surface upon which they are laid down is uneven, the individual layers tend to conform to that uneven slope. With continued deposition, the inequalities in slope become less, and eventually the angle at which the layers are deposited corresponds to the equilibrium position for the prevailing load and velocity of water. This initial dip of the sediments is usually small, but in areas of variable currents and on deltas it may be appreciable. In such places the dip varies in direction and amount and gives rise to cross-bedding. Variations in velocity of water ordinarily are greater in shallow water than in deep water; consequently cross-bedding is more likely to be indicative of a shallow-water origin of sediments than of a deep-water origin. Cross-bedding, however, can form in water of any depth, so long as variable currents exist at or near the bottom.

When streams enter the sea or lakes, the velocity is checked and part of the transported load is deposited. Unless longshore currents transport the debris away, deltas form. Deltas are flat and gently shelving on top near where the stream enters, but, at some point outward from shore, the flat top of the delta gives way to a relatively steep front, which is constantly built forward at essentially the same angle of slope as particles are swept forward off the flat part of the delta. At the base of the slope the layers flatten out. The three types of beds formed in this process are called top-set, fore-set, and bottom-set beds. In lakes or the sea, where the bottom slopes rapidly away from shore, the inclination of the fore-set layers, along the forward part of the delta, may be great; but in large bodies of water, where the water deepens gradually, the inclination of the fore-set beds is likely to be small. In fact, difficulty may be encountered in distinguishing fore-set beds from ordinary cross-bedding caused by variable currents. Geologists, when trying to determine the extent to which the angle of inclination of ancient sediments is due to initial dip, should bear in mind that initial dip in lakes is likely to be materially greater than in the sea. Steep initial dips commonly reflect diastrophism prior to deposition, which has led to the presence of relatively deep water close to shore or to the formation of an uneven bottom on which sediments are deposited.

WIND

Wind-blown or eolian deposits are essentially a characteristic of arid or semi-arid regions rather than of humid regions, because in arid regions the soil is poorly protected by vegetation and can be blown about by the wind. In present arid areas most eolian deposits consist of sand. However, during the Ice age, great masses of rock flour composed of fine particles of silt size, formed by the grinding action of the glaciers, were washed out by streams flowing from the ice and were deposited in great outwash plains (Thwaites, 1941). In the absence of vegetation these silt particles could be blown away by the wind. The extensive deposits of loess, which are found around the southern border of the glaciated area, in part are believed to have formed from such wind-blown silt. These loess deposits commonly weather in vertical cliffs, in contrast with wind-blown sand, which forms slopes of 30° to 35°, representing the normal angle of repose of incoherent material.

Wind-blown sand is well sorted because of winnowing action of the air which blows the fine particles away and transports the larger particles essentially by rolling or jumping along the ground. For a full discussion of eolian deposits see Bagnold (1941), Reiche (1945), and the papers in the Loess symposium (1945). Wind-blown sand is deposited mainly in dunes or hummocks. In this process the grains blow up the side of the dune on a comparatively gentle slope and then, as they pass over the crest where they are not supported by the slope, many particles come to rest on the lee side. Thus dunes are continually progressing in the direction in which the wind blows. If the wind changes, the inclination and direction of the layers of sand likewise change. Consequently dune deposits are characterized by cross-bedding.

ICE

Extensive deposits of glacial sediments are found in northern latitudes, in both North America and Europe. These deposits consist of three principal types: (1) groundtill, (2) morainal material, and (3) outwash. As the glacier moves along, it plucks up rock fragments and boulders of all sizes. In addition it scours the rocks over which it passes, producing much fine debris of silt and clay size. This fragmental material becomes embedded in the ice, and, when the ice melts, the debris settles on the surface of the land, forming deposits called groundtill. The thickness of this till ranges from a few feet to several hundred feet, depending to some extent upon the depth and past history of the ice mass. This till covers the ground like a blanket and is composed of particles of all conceivable sizes, from huge boulders many feet in length to finely comminuted clay. The rock fragments are angular in outline but commonly have rounded edges. The particles of clay size in some areas contain relatively little mineral clay. Thus the stability of the till is likely to be materially different than that of normal fine-grained deposits of lakes, rivers, or the sea, a point foundation engineers should bear in mind. An essential characteristic of till is the presence of numerous impermeable layers or zones which prevent the free flow of water.

A similar type of deposit called morainal material is laid down at the sides or in front of glaciers. The front of a glacier is maintained by a balance between the rate of melting of the ice and the rate of forward movement of the glacier. Commonly this balance is so even that the front of a glacier stays at one position for a long time. As the ice is constantly moving, the material carried with it is transported to the front of the glacier and is dumped when the ice melts. Thus big ridges called moraines are built up. Similar ridges form at the sides of the mass of moving ice. The material in these moraines is similar to groundtill.

Water-laid deposits also are associated with glaciers. The ice melts during summer, and the melted water finds its way along the surface of the ice, in places dropping down cracks to the interior or bottom. Eventually this water emerges from the side or front of the glacier and deposits its load in broad plains. As the water flows across these plains rapidly, the deposits are well sorted, and many of the particles of gravel size are well rounded.

Glacial deposits thus are characterized by a heterogeneous mixture of impervious and poorly sorted deposits interbedded with well-sorted, highly porous, and permeable sands and gravels. The geologist is of material service to the engineer in locating deposits of sand and gravel, close to their place of use, thus saving transportation costs. Moreover, the buried lenses of sand and gravel are good sources of underground water. (See Chapter 6.)

Lakes are common in glacial country. In the spring and summer, melting water transports a large amount of debris to the lakes. The coarse particles soon settle out and form sand or coarse silt deposits. In the winter, the lakes freeze so that no sediment can enter. Deposition is therefore confined to material largely of clay size which has stayed in suspension in the water during the preceding months. Thus a series of alternating coarse and fine deposits are formed (Antevs, 1922). These annual pairs of layers are called varves. The sand layers, being permeable, facilitate consolidation under load.

Gravity

Gravity is also an agent of deposition. In cold climates or in arid regions where differences in temperature between night and day may be extreme, fragments of rock are dislodged owing to differential thermal expansion and contraction of the rock constituents and of the water in cracks and pore spaces. If slopes are sufficiently steep or smooth, dislodged fragments roll down and come to rest at some lower altitude, forming piles of debris which generally have a slope of 30° to 35°. Deposits of this type are called talus and may attain considerable thickness if the blocks are not removed by other processes of erosion. Talus deposits oddly are rare in many arid regions, perhaps because the rocks disintegrate and occasional large floods wash them away.

In humid and temperate climates, alternate freezing and thawing of water in the pore spaces of soil or alternating periods of wetting and drying of the soil result in a slow creep of soil particles down slopes (Capps, 1941). In this process of creep, the constituents of the soil slowly change their position with respect to other constituents, thus changing the strength and stability of the soil.

Landslides are a manifestation of the effect of gravity. For details see Sharpe (1938) and Chapter 13 in this symposium. Soil and rock resting upon a slope start to slide when the weight of the overburden becomes greater than the strength or cohesion of the earth materials. Landslide deposits commonly are heterogeneous in nature because of the jostling caused as the material slides. Thus the sediment or mass of earth material is likely to be weaker than it was before the slide took place. Landslides commonly leave characteristic scars upon the hills, showing the places from which they slide, and the surface of the landslide deposits is hummocky.

Factors that affect landslides are the slope of the land, the strength of the earth materials, and the load that exists or is imposed. Loads can be imposed by adding material to the upper parts or by undercutting the lower parts. The type of clay minerals and the amount of water in the soil materially affect the strength of the soil.

Volcanism

Volcanic sediments consist mainly of layers of wind-blown ash. As eruptions of ash come at irregular intervals and as the distance to which the ash is transported varies with the wind, successive layers of ash vary in grain size. They also vary in chemical or mineral composition if the source of the volcanic material changes. Ash deposits commonly are interspersed with lava flows. Most deposits of volcanic ash contain bombs or fragments of rock and lava blown from the volcano. When these bombs land on newly deposited ash they bury themself in the ground, in many places more than one or two feet, and thus deform the layers upon which they land. The presence of these buried bombs leads to irregular consolidation when the overlying soil is loaded. Furthermore, volcanic ash commonly gives rise to montmorillonite clay, which has a great affinity for water and produces relatively weak deposits when wet.

Organisms

Sediments of biologic origin are essentially a product of environment, because living organisms are dependent upon environment for existence. Furthermore, since deposits consisting chiefly of organic material can form only when the rate of production of organic material is significantly greater than the influx of inorganic material, deposits of organic origin, such as coal, diatomite, oil shale, bog iron ore, or algal limestone, require special conditions of formation (Bradley, 1931; Bramlette, 1946; Cady, 1942; Harder, 1919). Deposits rich in organic matter commonly are relatively rich in radioactive material (Beers and Goodman, 1944).

CHEMICAL ACTION

Chemical action is essentially a question of degree of saturation. If water is undersaturated it can dissolve material; if it is oversaturated it can precipitate material. The principal factors are ionic concentration, temperature, oxidation-reduction potential, amount of water, microbial action, types of earth materials in contact with the water, and rate at which conditions change. Pressure usually is not a critical factor. Climate is a dominant influence because of its effect upon temperature, rainfall, and microbial action. Variations in moisture and temperature throughout the year or from one year to another strongly influence chemical reactions because of their effects upon equilibrium conditions and the degree of saturation of dissolved substances.

Evaporation changes the concentration of dissolved salts and thus changes equilibrium relationships. The distribution of water in the ground affects the oxidation-reduction potential. Earth materials lying above the water table tend to be more oxidized than corresponding materials lying below the water table. Changes in water level thus can significantly affect chemical reactions in the earth. Rate of flow influences the degree of saturation. Slow movement of water through pore spaces favors the development of a relatively high degree of saturation of dissolved substances, but, if the rate is so slow that the water becomes saturated, no further material can be dissolved. This feature has been brought out by Davis (1930) and others in respect to the development of cavities in limestone.

The concentration of the different ions, particularly the hydrogen-ion concentration, is an important factor. The presence of even a small amount of some minor element may significantly affect the solubility relations of other substances. Boron, for example, materially affects solubility of calcium carbonate in sea water. The solution of many substances is aided by the activity of microorganisms or soil-forming processes (Waksman, 1936; Jenny, 1941; Zobell, 1946). Microbial action is favored by warm and humid climate.

Parent earth materials vary greatly in their susceptibility to solution. Limestone is readily dissolved by acid solutions and volcanic ash by basic or alkaline solutions. Salt, gypsum, nitrate, and other products of chemical evaporation are dissolved by moving water of almost any character.

Chemical deposition is essentially a question of environment. The chief requirement is the development of a condition of oversaturation. The temperature, pressure, or concentration of dissolved substances must change before material can be precipitated. If the solutions are supersaturated, foreign material sometimes needs to be added to start the precipitating action. Evaporation is the chief cause of changes in degree of saturation, though microbial activity or the addition of other substances, such as iron, manganese, or silica from submarine or surface springs, may also influence the solubility relationships. The oxidation-reduction potential, as mentioned above, is also a factor, especially with respect to the development of red color in rocks (Tomlinson, 1916).

ENVIRONMENT

Interrelation of Factors

Deposition of sediments, as has been pointed out above, is influenced very strongly by environment. An environment of deposition may be considered an area in which the combined effect of the fundamental factors of topography, temperature, water, organisms, and rates of change of conditions are similar. Depending on the degree of similarity of factors, subenvironments exist within general environments. The ocean has many characteristics in common throughout the world, but different parts vary. The Gulf of Mexico, for example, is quite different from the Bay of Fundy.

The fundamental factors that affect environment are interrelated. Changes in one factor result in corresponding changes in other factors, sometimes to a marked degree. The shape of the land influences precipitation and flow of water and its resulting effect upon erosion, transportation, and deposition of debris. Topography affects the climate and hence the activity of organisms.

The distribution of water influences the shape of the ground by its action on erosion and deposition; it affects the climate by its influence upon precipitation, evaporation, and the transfer of heat from the tropics toward the poles through the medium of oceanic circulation. Moreover, the distribution of water influences the activity of organisms by its effect upon food supply and distribution of oxygen and carbon dioxide.

Temperature profoundly influences all other factors, primarily because it is a source of energy. Climate is a direct result of the distribution of temperature and precipitation. Wind and rain are closely dependent upon temperature, and these two agents in turn profoundly affect erosion, transportation, and deposition and thus the shape of the land. Even diastrophism may be regarded as resulting from changes in distribution of temperature within the earth.

Living organisms and plants influence the configuration of land because of their effect on erosion and on chemical action, which results in changes of the shape of the land. Organisms affect the distribution of water by transpiration and by increasing the infiltration of water into the soil. Their plentifulness or scarcity modifies the rates at which environmental conditions change.

Changes in environmental conditions in turn influence the environmental factors themselves. Diastrophism, or deformation of the earth, exerts a dominant influence upon environment, either directly by altering the shape of the land and the distribution of water, or indirectly by modifying the climate and thus in turn the rate of erosion, transportation, and deposition. The movement of water, particularly currents in the sea, is greatly influenced by diastrophism (Bailey, 1936; Krynine, 1940).

Oceanic Processes

The chief locus of deposition of sediments is the ocean. Any person attempting to study deposition in the sea should be familiar with the general principles of oceanography. For a comprehensive description see *The Oceans,* by Sverdrup, Johnson, and Fleming (1942).

The surface temperature of the ocean is high near the tropics and low near the poles. The temperature of the water decreases with depth in all latitudes, but below a depth of 5,000 feet it is remarkably constant with respect to latitude, being everywhere less than 40° F. at that depth. As the temperature of sea water decreases, its density increases. Heavy water cannot long overlie light water; it must sink to a level where it encounters water of its own density. Thus, once cold and heavy water has sunk to a lower level in the sea, special conditions must develop to cause it to rise to higher levels. Hence the water in the ocean is essentially stratified with respect to density. Water within individual layers is free to move within that layer. In fact, in some places water at different depths is flowing in different directions. Water moving at a given level may be deflected upward as it passes over a ridge. The effect of submerged ridges on the turbulence and the vertical motion of water is similar to the effect of mountain gaps on wind. This disturbance of water over ridges results in winnowing of the finer particles and causes the sediments on ridges to be more coarse-grained than those upon adjoining slopes in deeper water (Trask, 1932). No matter what the depth of water, the sediments on the Mid-Atlantic Ridge in more than 10,000 feet of water are materially coarser than those on either side of the ridge (Bradley *et al.,* 1942).

Evaporation of ocean water increases the density. If the density increases, a column of water of unit height and cross section weighs more than a column of lighter water of the same height and unit cross section, with the result that water tends to flow from the more dense area to the less dense area. This process of adjustment of mass together with the wind causes the great ocean currents, such as the Gulf Stream and the Japanese current. Owing to the rotation of the earth, currents are deflected to the right in the northern hemisphere and to the left in the southern hemisphere.

The wind generates currents and tends to pile water up ahead of it, thus overbalancing the water in front with respect to the water behind. As a consequence the surface water in front sinks and the water behind rises, bringing the deep water to the surface. This deep water is rich in mineral nutrients needed for the microscopic plants, the plankton, which are the basic source of food in the sea and of organic matter in the sediments beneath. Upwelling of this sort is common off the coast of California.

The ocean currents convey warm water from the tropics toward the poles and thus affect the temperature of the air, which in turn influences the movement of the wind, which then affects the motion of the water. Thus the ocean, like a dog chasing its tail, is constantly trying to attain a condition of equilibrium but never does. However, in many parts of the ocean the rates of change on the average are fairly constant; so a condition of dynamic, in contrast with static, equilibrium is obtained. This general circulation of the water has profound effects upon climate, the growth of organisms, the concentration of dissolved substances in the sea, and thus in turn upon the deposition of sediments.

Currents, however, are produced in the sea in several other ways. Waves approaching the shore diagonally pile the water upon the beach at an angle with the shore, and the water descending from the beach reaches the sea at some point downwind from where it first struck the beach (Munk and Traylor, 1947). Thus a longshore current develops which may have a profound effect upon transportation and deposition of debris, particularly in areas in which the wind blows mainly from the same general region.

Tides produce currents in shallow water. The large tsunamis which are reported to be caused by earthquakes conceivably could also set up currents. In water less than 600 feet deep waves can stir up the bottom and winnow the sediments (Stetson, 1938; Shepard, 1932, 1948). Internal waves, developed in layers of denser water beneath the surface, conceivably could generate currents. Coarse sediments in deep water in some areas may have resulted from such currents (Revelle, 1944; Sverdrup Anniversary Volume, 1948, pp. 673, 683).

DEEP SEA

The ocean contains several distinct environments of deposition with respect to supply of mechanical and chemical constituents, distance from land, character of water, and configuration of the basin of deposition (Murray and Renard, 1891). In the deep sea far from land, the rate of supply of mechanical debris is low. The sediments consist principally of material of organic or wind-blown (eolian) and cosmic origin. Relatively little material is now being precipitated in the deep ocean. Water shallower than 15,000 feet, however, apparently is saturated with calcium carbonate in some areas. Thus calcium carbonate perhaps is now being precipitated chemically, though most of the carbonate seems to be of organic origin. The ocean water below a depth of 20,000 feet at present appears to be undersaturated with calcium carbonate. As a result, particles of calcium carbonate seemingly dissolve as they settle to the bottom. The sediments contain little calcium carbonate. The undersaturation of the deep water in the ocean, however, should not be considered a reliable index of past conditions, because the present state almost certainly is due to the addition of cold and dense water to the bottom of the ocean during the Ice age. As this cold water sank during Pleistocene time it must have displaced upward, or cooled, the water that formerly lay at the bottom of the ocean. The deep water in other geologic periods may well have been materially warmer and more thoroughly saturated with calcium carbonate than is the present water. Consequently some ancient limestones may be of deep-water origin.

Radiolarian chert is considered by some people to be of deep-sea origin, because at present radiolarian deposits are found principally in deep water. Siliceous deposits of this type represent a relatively rapid rate of deposition of silica with respect to terrigenous debris (Davis, 1918). Such conditions most certainly can prevail in deep water far from shore, but they also could exist in basins near shore if the adjoining land areas supplied little debris and if an excess of silica were supplied the sea from submarine sources. Some of the radiolarian deposits of the Franciscan formation of California may be of shallow-water origin.

Coarse sediments can be found far from shore in deep water, as indicated by the poorly sorted glacial marine deposits reported by Bradley and Bramlette (Bradley *et al.*, 1942) from the North Atlantic. These sediments contain terrigenous constituents of ice-raft origin.

Basins

Deposits in basins, either in the ocean far from land or near shore, are of many types. The depth of the sill in these basins influences very materially the conditions in the basin and thus in turn the deposits. The sill may be defined as the outlet of the basin if sea level were lowered to the extent that the water in the basin would be entirely enclosed by dry land. If the sill is deep, the water below sill depth is more likely to escape than if the sill is at shallow depth. The water in basins with deep sills, therefore, is less apt to become stagnant. The oxygen content of the water in any basin, however, ordinarily will be less than in the overlying water, and the sediments are likely to be in a higher state of reduction than similar deposits laid down in more open places on the sea floor. The organic content is apt to be relatively high, as the lowered oxygen content inhibits the decomposition of organic matter.

Basins favor chemical precipitation, because the lack of circulation or the poor circulation favors the increase in concentration of dissolved substances to such an extent that a state of saturation develops. The addition of chemical substances such as silica, iron, or manganese from submarine springs is more likely to result in the formation of chemical deposits in basins than in other places.

If the sill is relatively shallow and the basin relatively deep, vertical circulation, or ventilation of the water as it is called, is much inhibited, and the water becomes stagnant (Strøm, 1939). Hydrogen sulphide is formed, and highly reduced sediments rich in organic deposits are laid down. If the rate of influx of terrigenous debris is small, deposits largely of a chemical nature form in basins. Extensive deposits of salt, gypsum, potash, phosphate, and limestone may form in this way (Lötze, 1938). Alternations of the level of water above or below sill level or specially favored areas of evaporation, like the Gulf of Kara Bugaz in the Caspian Sea, favor the influx of chemical ingredients and ensuing concentration to the point of precipitation. Unfortunately examples of basins of many of the types of chemical deposits formed in the past do not exist today. Certainly no areas are known where dolomite is now forming (Sander, 1936). Geologists in endeavoring to determine the mode of origin of saline and other chemical deposits would do well to consider carefully the fundamental principles of oceanography as manifested by the present ocean.

Geosynclines

Geosynclines have many characteristics of basins (Jones, 1938), though they are not necessarily enclosed in character. In fact they are simply low areas in which thick deposits of sediments accumulate. Because of the presence of cross-bedding, ripple marks, and alternations of sand, silt, and clay, many people regard geosynclines as essentially shallow, but they may be deep in part. Recent work in the Gulf of Mexico (Sverdrup Anniversary Volume, 1948, p. 683) has shown that cross-bedded sand and silt are found in deep water in the middle of the Gulf of Mexico. More likely, the depth at which the deposits form in a geosycline represents a balance between rate of sinking of the basin and rate of influx of debris.

When studying the origin of sediments in ancient geosynclines, geologists should consider the fundamental factors of quantity and quality of debris supplied the basin, particularly the size of the particles, and the probable currents that influenced the deposition of the sediments, especially the possibility of longshore currents which could transport debris far from the mouths of rivers that supplied the detritus. An understanding of the shape of the geosynclinal basin should also help in interpreting the mode of origin of the sediments.

Continental Slope

Deposits on the continental slope, that is, on the slope from the flat continental shelf down to the abyssal deeps, are conditioned by the distance from land, the existence of currents or turbulence along this slope, the angle of slope, and the type of debris supplied. The deposits in general are fine-grained, but they may consist of sand. The sediments also may have unusual skewed size distributions in places where material swept from the adjoining flat continental shelf is added to the normal supply of debris that is deposited. The angle of slope ranges from less than 1° to more than 10°. If the deposits are relatively fine-grained, as they are likely to be, conditions of instability of slope may prevail, with the result that considerable slumping may take place (Fairbridge, 1946). Deposits in which the layers of sediments seemingly have been deformed contemporaneously with sedimentation, therefore, may be continental slope deposits. Some of the Franciscan sediments, which are so badly distorted, may have such an origin.

Continental Shelf

A continental shelf extends outward from shore, 10 to 500 miles in many parts of the world (Shepard, 1932). This shelf slopes only a few feet per mile and is characterized by relatively coarse, well-sorted deposits, mostly of sand or coarse silt size. As the water at the outer edge of the shelf is 300 to 600 feet deep, the floor of the shelf is within the reach of wave action during times of heavy storms. Undulations in the continental shelf influence materially the texture of the deposits. The fine material tends to concentrate in depressions on the shelf. Ridges or masses of sediment that rise above the general level of the platform are found on the continental shelf in several places, especially the Gulf of Mexico, the Atlantic Coast, and the North Sea. Some of these ridges may represent former shore lines when the sea stood at a lower level than it now does, but they also may represent submerged masses of sand which migrate across the shelf just as dunes march over the land (Lüders, in Trask, 1939, p. 337).

BEACHES

Beach deposits are of many different types, depending primarily on the configuration of the land and the strength with which waves can strike the beach. Where the ground slopes very gently both seaward and landward from shore, as in the Gulf of Mexico along the Texas coast, the beach deposits are very fine-grained. Not only is the size of particle supplied the sea of relatively small size, but also the gentle slope of the sea bottom interferes with the progress of large waves toward the beach. However, whether the flat slope is the result or the cause of the distribution of sediments is a question. Geologic textbooks speak of a profile of equilibrium, but they do not correlate the angle of slope of the profile with the distribution of energy in the waves, or with the size and amount of material available for transport by the waves. It seems as if the profile depends very much upon the supply of debris, which in turn is influenced by the distribution of currents and the overall configuration of the locus of deposition. Certainly the angle of slope of beaches is related to the size of the constituent particles. Steep slopes tend to have coarse particles, and gentle slopes fine particles; so why does not the same relation apply to the shallow water off shore?

Beaches are influenced greatly by longshore currents, which in turn are influenced by the direction of prevailing wind (Munk and Traylor, 1947). Particles of sand are transported along the shore and form spits and bars (Gilbert, 1890). The waves and currents tend to cause the edge of the beach to migrate shoreward, particularly during time of high water and strong waves. Whether or not a beach erodes or builds seaward depends on whether sand is supplied the beach at a slower or faster rate than it is removed from the beach. (See Chapter 15.) In general a sort of dynamic equilibrium prevails.

BAYS

In areas where sea level is rising or has risen recently, the mouths of streams become drowned and form bays. The tides pass in and out of the mouths of these bays. The water in most bays is shallow, and the diurnal movement of the tide keeps the water muddy. (See Chapter 16.) The position of places of maximum velocity of tidal currents changes from time to time, thus causing continual erosion and deposition of sediment in the bay. Silt and clay are deposited in quiet water, and sand or coarse silt is laid down in or near the channels. The sediments are poorly sorted and vary greatly in texture from place to place. The tidal flats are exposed during low water, and the sediments alternately take on and lose water as the tide comes and goes. Organisms ingest the sediment in search of food. The deposits, therefore, are irregular in character, bedding, and strength.

AREAS OF CALCIUM CARBONATE DEPOSITION

Limestone is formed in several types of environments. Saturation or relatively high concentration of calcium carbonate in the water, however, is common to all types. In addition the rate of influx of terrigenous debris must be comparatively slow with respect to rate of deposition of calcium carbonate. Concentration of calcium carbonate in water is favored by increase in temperature and salinity and decrease in hydrogen-ion concentration (increase in pH) (Wattenberg, 1933; Trask, 1937). Calcium carbonate may be precipitated directly from supersaturated water; it may be formed by bacteria or algae as a part of the metabolic processes by which the organisms get food and energy from the water; or it may be formed from detrital shell particles. Precipitation of calcium carbonate from saturated or supersaturated solutions is favored by the presence of solid particles of calcium carbonate or other material. In places this process produces small spherical pellets which are called oolites (Brown, 1914).

The most favorable environment of deposition of calcium carbonate is a shallow flat-bottomed sea adjacent to a low-lying coast in a tropical or semi-tropical climate, as for example the southern coast of Florida (Vaughan, 1910). Other environments are lagoons, atolls, coral reefs (Emery, 1948), or even the deep sea where the water is less than 20,000 feet deep. (See Chapter 33 in this symposium.) Calcium carbonate may even be deposited from saturated water in lakes (Russell, 1885). The activity of organisms is a potent influence in the deposition of calcium carbonate in lakes.

RIVERS AND DELTAS

Many different types of environments of deposition are found on land. For the world as a whole, terrestrial deposits are less plentiful than marine deposits; but in places, notably in Wyoming and Colorado, thick non-marine deposits have accumulated in the past. These sediments are mainly the result of stream action. The essential requirement is the formation of a place of deposition, particularly a flat surface upon which the rivers can deposit their load at times when they get out of their channels.

Most deposits laid down by running water on land are poorly sorted and poorly stratified, except in channels where currents are relatively strong and uniform. Most river and flood-plain deposits vary in thickness and are cross-bedded. Alternations between coarse and fine deposits are common.

River deposits are characterized by cut-and-fill action during flood. (See Chapter 18.) When the discharge is great and the velocity of the water is high, the bed of the stream is scoured to a greater depth than during normal periods of flow. As the flood abates and the stream returns to normal levels, the depth of scour diminishes and the bed fills up to its customary position. Large streams may be scoured more than 50 feet, as is indicated by boards found during constructions of piers, or by the undermining of deep piers during floods. In constructing caissons in rivers, geologists and engineers should endeavor to determine the depth to which the river scours during floods and design foundations accordingly.

At time of flood, streams rise above their channel and spread across the adjoining flat land, leaving deposits of silt and sand (Fisk, 1944). Deposits of this type ordinarily are not well sorted and tend to vary in grain size and thickness from place to place both longitudinally and laterally across the flood plain. Deposits commonly are thickest at the boundary between the channel and the flood plain, because decrease in velocity of the water at such places favors the deposition of sediment. This process results in the formation of natural levees.

The deposits at the mouths of large streams likewise are irregular. Sand alternates with silt and clay almost indiscriminately both laterally and vertically. The sediments are poorly sorted and commonly are mixed with plant fragments (R. J. Russell, 1936). Thick deposits build up off the mouth of the stream unless longshore currents carry the debris away. A factor in the development of longshore currents is the rate at which the delta sinks. If the rate of sinking is rapid, the mouth of the delta becomes embayed and longshore currents cannot effectively remove the debris until the delta builds forward to a point where the longshore currents can sweep the shore.

In the Mississippi delta in some places, masses of clay rise up through the sediments to form mud lumps or mud boils (Shaw, 1913). The mud is pushed up in much the same way as mud rises in front of an embankment which fails because of overloading. Perhaps a similar overloading due to natural causes takes place in deltas. At any rate, displacement of masses of mud in this manner, if found in ancient sediments, might well be interpreted as evidence of contemporaneous diastrophism when it really was only a readjustment of unstable sediments due to imposed loads.

DESERT AREAS

In desert or semi-arid regions, rainfall is characterized by infrequent but intense storms of local extent. After such storms the water commonly flows down the slope of the land in a sort of sheet, resulting in the formation of gently sloping cones (Paige, 1912; Lawson, 1915; Woodford, 1925; Bryan, 1936; Gilluly, 1937). The shape of the cone seems to be a function of the average load and the average velocity of water during time of flood. If irregularities protrude above the level of the surface of equilibrium they are worn away; if irregularities extend down below the surface of equilibrium they are filled up. The upward ends of the fans abut against a steep mountain slope or merge into a stream coming down through a valley in the mountains. As the mountain surface is eroded backward or as the upward end of the fan moves mountainward, the relationships of load to average discharge and to profile of equilibrium change, with the result that deposits tend to accumulate in the lower parts of the fan and to be thin on the upper parts. The thinly covered rock surfaces on the upper parts of fans are called pediments.

The deposits generally consist of two sizes of particles. The larger group of particles consists of angular or subangular fragments of rock, commonly ranging from 1 to 10 inches in diameter; and the smaller group consists of particles of coarse sand or fine gravel size. The larger particles ordinarily form less than 25 percent of the weight of the rock, and the finer particles more than 75 percent. Apparently the size of the smaller particles is a function of the transportive ability of the water. The size of the larger particles seemingly is governed by the capacity of the water to push them along over the smaller particles, which act somewhat like roller bearings.

At the lower end the fan merges into a more or less broad valley filled with alluvium, or the fan may pass gradually into a playa which, during times of flood, is converted into a lake. The playas are exceedingly level and are dry most of the time. The lakes that occupy them during and after a flood are broad and shallow (Russell, 1885). The relative frequency of floods, the supply of debris, and the size of the playa govern the types of deposits that are laid down. The sediments vary in texture from layer to layer, but in general they are fine-grained. A variety of organic deposits depending on food supply and length of time required for the lakes to dry up is laid down. Some of the playas, such as Searles Lake in California, give rise to economic deposits of potash, salt, and borates (Foshag, 1926).

Many of the streams in the semi-arid parts of western United States occupy broad valleys filled with alluvium. This alluvium consists of several different kinds of layers, some of which are discolored brown or black on top, and they probably represent more or less long intervals during which soil developed. Some of the layers are remarkably uniform in thickness for a distance of a mile or more. The layers are lenticular and presumably represent deposits of single floods or of single periods of similar climate. The texture of the deposits ranges from clay to sand. For further information see Chapter 23.

This alluvium has been subjected to alternate periods of fill and scour. During periods of scour, deep gullies form which in time swing laterally to erode some of the fill previously deposited in the valley. At the present time a period of scour characterizes most of the Southwest, particularly New Mexico, Arizona, Wyoming, and Utah, but only to a relatively small extent central and eastern Nevada and central California. The cause of the present scour has been attributed to overgrazing, but it can also develop from natural causes, because as Peterson shows in Chapter 23 of this symposium there have been at least three periods of scour and subsequent fill since Late Pleistocene time, caused by geologic agencies alone.

SWAMPS

The stagnant water in swamps favors the accumulation of woody and other types of plant material that give rise to coal deposits (Cady, 1942). Such environments commonly are found near the outer edges of coastal plains, particularly in areas bordered by barrier beaches or bounded by deposits laid down in distributaries of deltas. The essential feature is the empoundment of water in a broad, low area in which vegetation, particularly trees, can flourish. Depending upon the relative distribution of wooded and open areas, different types of organic material accumulate. In the wooded areas the material consists principally of the partially decomposed fragments of wood embedded in a matrix of more or less completely decomposed woody material. This matrix has some of the characteristics of a colloidal gel of organic material. With time, such deposits give rise to ordinary coal. In the open areas pollen and spore material may collect. Such deposits ultimately form cannel coal. In places, particularly in open water, algae may develop luxuriantly and give rise to beds of boghead coal or oil shale. The essential feature in the formation of any particular type of coaly material is the relative abundance of woody, spore, and algal material preserved in the sediments. Thus distribution of wooded and open areas, types of plants present, length of time stagnant conditions prevail, rate of influx of terrigenous material, and subsequent geologic history are essential factors in the formation of coal.

Lakes

Lake sediments are influenced materially by the nature of the water in the lake. Geologists interested in lacustrine deposits should be familiar with the fundamental principles of limnology, as there are many different types of lakes (Welch, 1935; Bradley, 1948). Critical factors are average temperature of water, extremes of temperature, quantity of rainfall, seasonal and cyclic distribution of rainfall, activity of microorganisms, concentration of dissolved materials, size and shape of lake, depth of water, and supply of detritus. The seasonal variations in temperature of the water profoundly influence the type of deposits. Fresh water attains its maximum density at 39° F. As the surface water approaches 39° F. it becomes heavy and sinks to the bottom of the lake, forcing the bottom water upward. In the more northern latitudes this phenomenon happens twice a year; once in the spring as the surface water warms up to 39° F., and again in the fall when it falls to 39° F. As the deeper layers of water commonly are relatively rich in organic matter and mineral nutrients, plant life tends to increase when this deep water rises to the surface in the spring. However, if during the summer months the activity of microorganisms has consumed all the dissolved oxygen in the lower water, hydrogen sulphide is formed, which, when it rises to the surface during the spring and fall turnovers, may kill a considerable part of the life in the lake.

In more tropic areas, temperature of the surface water never falls below 39°, with the result that the deep water does not rise to the surface. Thus, a permanent state of stagnation may be produced in the deep water, in which hydrogen sulphide can be continually present and only a few types of organisms, particularly certain anaerobic bacteria, can live. A heavy storm or a rare cold spell may cause some of the deep water to rise to the surface, killing off much of the life.

This influence of the temperature on the density of water influences materially the type of organisms that grow in the lake and hence the chemical equilibrium of the dissolved materials. Lakes that are periodically ventilated by overturning of the water are in a relatively high state of oxidation compared with those in which the water does not turn over. The depth of water, however, is a factor, because, the shallower the lake is, the more likely the bottom water is to be stirred up during a storm.

In some lakes algae develop luxuriantly, giving rise to deposits of organic matter, which in the course of time may form deposits of oil shale (Bradley, 1931). The organic matter, when first deposited, has a very high water content, but oil shale generally is found in very thin layers, which indicates a high degree of consolidation or compaction during the course of geologic time. As Bradley has shown, layers of oil shale commonly are of a dual nature, one part representing summer conditions, and the other winter conditions. Thus, oil shale, at least the Green River oil shale, resembles varves formed in glacial lakes.

The deposits in lakes are likely to be cross-bedded and highly variable near shore, particularly on the deltas where streams flow into lakes. The larger lakes have bars, spits, and beaches, which have essentially the same characteristics as corresponding features in the ocean. The sediments laid down in the central parts of the large lakes, like sediments in the open sea, are relatively fine in texture, and are comparatively well stratified; however, lacustrine deposits commonly change in texture and character from one layer to another.

DIAGENESIS

Sediments change after they have been deposited. The water is squeezed out of pore spaces owing to the effect of superimposed loads, thus causing a reduction in thickness. This compaction of the deposits presses the constituents more firmly together and gives the sediments greater strength. Materials are deposited in the pore spaces and cement the particles together. New minerals form and old minerals grow by the addition of new material. Ultimately the sediment is consolidated into rock. The sum total of these processes is called diagenesis. Diagenesis, however, is to be distinguished from metamorphism, which results in the more or less extensive formation of new minerals as a result of dynamic stress, comparatively high temperature, and mineralizing solutions.

At present the processes of diagenesis are not well understood. Compaction of sediments, with resulting decrease in porosity, is clearly related to the imposed load and starts as soon as the sediments have been deposited. *Compaction* is used by geologists in essentially the same sense as the word *consolidation* is used by soil mechanics engineers. The water content of the sediments, or, more appropriately, the porosity, is directly related to the texture of the sediments. Clays have a high initial water content compared with silts or sand and thus compact more than silt or sand. For sediments to compact, the water must be squeezed from the deposits. The permeability, therefore, is a big factor in the rate of consolidation. Sands, being permeable, have a high initial rate of compaction compared with clays, which are relatively impermeable. In fact, sands ordinarily compact very quickly to the point where each grain is in contact with one or more other grains; after this they compact very slowly as grains are deformed or rotated so that adjoining grains can nestle more effectively into available pore space. Clays likewise compact more rapidly at first, but, after the initial period of rapid forced removal of pore water, they compact very slowly for a long time, as the pseudo-anticlinal structure of sediments over buried hills indicates (Athy, 1930; Hedberg, 1936). Essential factors in this compaction are load, grain size, permeability, and time.

During consolidation of the sediment into rock, that is, while water is being squeezed out, the strength or ability of the sediment to support a load is affected to a considerable extent by deformation of mineral constituents, which causes the individual constituents to be more firmly locked together. While this process is going on, but particularly after the initial stage of settlement, material is precipitated from the pore water and thus binds the constituents together. The concentration of dissolved substances, the rate of movement of the water, the solubility relationships of the dissolved materials, base exchange, rock pressure, activity of microorganisms, size and shape of the pore spaces, and mineral composition of the rock particles all influence the precipitation of cementing materials. Commonly these materials are laid down in pore spaces between grains, but in places zones of cement are deposited around some focus of precipitation until a nodule or concretion is formed. The causes of localization of precipitated material in the pore spaces of sediments is at present poorly understood, but it is of great importance in interpreting the migration of oil and also the origin of ore deposits in permeable rocks. (See

Chapter 29.) The mineral constituents of sediments dissolve or grow to such an extent that as time goes on the grains are locked more firmly together, with resulting increase in strength of the rock. A great variety of minerals are known to be generated in sediments, but the controlling factors of formation of new minerals are not yet completely known. (See Chapter 25 in this symposium, and Pettijohn, 1949, pp. 476, 500.)

CLASSIFICATION

Nomenclature of sediments is a complicated subject, principally because so many different attributes are used in classifying sediments. Many systems of terminology have been described among which may be mentioned those of Allen (1936), Casagrande (1947), Grabau (1913), Jenny (1941), Krumbein and Pettijohn (1938), Krynine (1940), Pettijohn (1949), Rutledge (1940), Twenhofel (1932, 1937), Udden (1914), Wentworth (1935), and Wentworth and Williams (1932). Most systems represent a combination of descriptive and genetic factors. However, in so far as possible, a classification should be descriptive, because a genetic classification is based on some sort of conception of the mode of origin of the deposit based on descriptive properties. Three main groups of sediments are generally recognized: (1) clastic deposits, composed principally of particles that have been transported mechanically and then deposited; (2) chemical deposits, composed mainly of materials precipitated from solution; and (3) organic deposits resulting from the activity of organisms.

Some deposits such as limestones overlap all three groups. Limestones can be composed of particles transported by water, ice, or wind from some limestone area and then deposited; they may form directly as a result of chemical action; or they may result from the metabolic process of organisms. The end products in all three processes may be similar. The mode of origin, therefore, might be ascertained only after careful study, and perhaps not then. Siliceous deposits may also be difficult to classify, particularly after they have been subjected to percolating waters which have dissolved and reprecipitated various materials. However, most deposits of chemical origin, such as salt, potash, gypsum, chert, and some iron deposits, as well as organic deposits of coal, oil, shale, and even petroleum, can be classified so clearly that no further discussion is needed here. The principal confusion exists among the clastic or mechanical deposits.

The clastic deposits are classified mainly upon the basis of the grain size of the major constituents. The names gravel, sand, silt, clay, and colloid are universally adopted for classifying individual constituents by size. Fairly good agreement regarding boundary between size groups has been achieved, particularly for sand particles, which almost everybody agrees range between 64 microns (0.064 millimeter) and 2 millimeters in diameter. The lower limit for silt generally is set at 4 or 5 microns. Workers interested in classifying sediments into size groups whose upper and lower limits have geometric dimensions prefer 4 microns as the upper limit for clay because it makes the classification so much easier to handle statistically; but some workers interested in the physical properties of clays prefer to use 5 microns for the upper limit of clay because that size marks a division point between recognizable physical properties, based principally on the properties of clay minerals, which commonly do not reach much beyond 5 microns in size.

Most people set the boundary between clay and colloid between 0.5 and 1 micron; but, as particles of this dimension are difficult to measure accurately and as the actual content of colloids is not yet a matter of major importance for most practical applications of sediments, people have not argued much over the lower limit of clay size.

Sediments are composed of particles of many different sizes. Geologists are accustomed to classify the deposit upon the basis of the diameter of the average (median) particle, the D_{50} of the engineer. The median is the diameter for which one half of the weight of the sediment is composed of particles of larger size and one half of particles of smaller size. It represents the mid-point on the grading curve. If the sample is well sorted, that is, if most of the particles are close to the median, little difficulty in classification exists, but, if the sample is poorly sorted and contains a large amount of material larger or smaller than the median, the tendency is to use a modifying adjective. Thus a sample having a median diameter of 15 microns and containing 25 percent clay would be called a clayey silt. Difference of opinion exists about how much of the lower or larger grade size need be included to warrant the use of a modifying adjective. In practice the amount ranges between 10 and 30 percent. As a rule workers use the name that most conveniently fits the purpose for which the work is done. Casagrande (1947) has adopted an arbitrary series of limits of particle size and has given corresponding names to sediments of given size distributions. Soil mechanics engineers find this classification useful.

The shape of the constituents is used in classifying sediments composed chiefly of particles larger than sand in size (Wadell, 1935). If rounded, the deposits are called gravel; if angular, they are called breccia. Mineral or rock composition also is used for some of the coarser deposits. Coarse deposits consisting primarily of material of granitic origin, in which the rock and mineral fragments are distributed in essentially the same proportion as in the original rock, are called arkoses. The term graywacke is used by some for a sandstone composed mainly of feldspar and quartz embedded in a clay matrix, but others use the term to indicate material derived from basic rocks in contrast with arkose, which is derived from acid rocks.

The proportion of calcium carbonate in a sediment causes confusion in terminology. A sediment should contain at least 30 percent calcium carbonate to be called limestone. If it contains between 10 and 30 percent the sediment is commonly called a calcareous sandstone or shale, depending upon the average grain size of the clastic constituents. Some workers object to the use of the term calcareous for this purpose, as they would like to distinguish a sandstone or shale cemented together by calcium carbonate from a sediment in which detrital particles of calcium carbonate are intimately mixed with particles of terrigenous origin.

Confusion also exists with respect to names for the sediments after they have been consolidated into rock. A consolidated sand is almost invariably called a sandstone, but a silt is classed as a siltstone or shale, depending on the degree of lamination of the rock. If massive, the rock is called a siltstone; if laminated, it is called a shale. Deposits of clay particles similarly are designated as mudstone and shale, respectively. If a worker is concerned about misinterpretation of the terms, he should describe the basis for the classification he uses.

IMPACT OF SEDIMENTS ON PRACTICAL ENDEAVOR

The practical applications of sediments depend on the properties of the sediments and the processes that affect them. The strength of sediments and the changes in strength under added or reduced stress are of fundamental importance to the construction engineer, whether he be interested in bearing strength of foundations, stability of slopes, or the construction of tunnels (Terzaghi and Peck, 1948; Taylor, 1948). The strength of loosely consolidated sediments and earth materials depends on the water content, the grain size, the mineral composition (particularly the type of clay minerals), the stresses to which the sediments have been subjected, and the length of time the stresses have been applied.

The water content depends on, among other factors, the load, the grain size, and the clay mineralogy. The greater the load and the longer the load has been applied, the lower is the water content and the less the response of the sediment to added load or added stress. The more permeable a bed is, the more rapidly the water is forced out of it and the more quickly the sediment comes into equilibrium with the stress applied. The finer the sediments and the more poorly they are sorted, the higher is their uniformity coefficient and the less permeable they become.

When considering the release of pore-water pressure under added stress, the engineer and geologist would do well to look on this condition as a *dynamic* state and not as a *static* state. The water moves between the constituent grains, thus forming a greater proportion of the unit volume of a sediment in some places and a lesser proportion in others. If the stress continues long enough or is sufficiently strong, shear cracks develop through which water can move. Thus any measurement of shearing stress made in the laboratory must be interpreted in light of conditions as they exist in the ground. A laboratory test may indicate a high angle of internal friction, but, when a load is placed upon the sediment in the field and the water begins to move through the constituent grains, the relations of water to individual grains change. The engineer should realize that, if the water forces its way between the grains so that the grains do not come to rest upon other grains in as many contacts per grain as they did previously, the shearing stress at such places becomes less and, if several such places should suddenly develop in a plane, a very different condition of shearing stress results than during a laboratory test in which the movement of the water within the sediment sample may be materially different from that in the field. It is perhaps for this reason that the apparent angle of internal friction is low along the planes on which sediments sometimes fail.

Clay minerals differ in their affinity for water. Individual mineral grains or flakes of clay react differently to water under different concentrations of cations in pore water (Grim, 1942; Kelley, 1939). This subject has not yet been thoroughly explored, but it is one that should be considered seriously by the engineer when working in areas where previous construction experience is scanty. (See Chapter 25.) Very likely the different relationships between liquid limit and plasticity index described by Casagrande (in Terzaghi and Peck, 1948, p. 36) depend upon the type of clay mineral. Otherwise why should all the sediments in a given area show such a constant relationship between liquid limit and plasticity index, whereas all the sediments in another area exhibit a different but equally consistent relationship?

Alternating freezing and thawing of the ground in cold climates materially affects the strength of the sediments. As Black shows in Chapter 14, this question is essentially one of dynamic relationship between water and ice within a sediment.

The permeability and porosity of sediments are of great practical importance to petroleum and mining geologists, to ground-water hydrologists, and also to construction engineers, because the movement of oil and water through ground depends so much upon the permeability (Meinzer, 1923; Muskat, 1937; Tolman, 1937; also Chapters 4, 6, and 32 in this symposium). Once again it should be mentioned that *permeability* is influenced by the size and degree of sorting of the constituent particles; *porosity* depends upon the size and shape of particles and upon the load or degree of compaction (consolidation) of the sediments. For example, it is well known that the water content of a clay may be higher than that of a silt or sand but the permeability may be less. Clays normally do not have a low porosity unless they have been compacted for a long time. Permeability is of material significance to the mining geologist because the ease with which mineralizing solutions and gases can penetrate rocks, particularly sedimentary rocks, in many places is a major factor in determining whether commercial ore deposits will be precipitated in the sediments. (See Chapter 29.)

Both the physical and chemical properties of the constituent minerals concern mining geologists in search of ore minerals. The manufacturer also is interested in the nature of the sediments as sources of raw materials, as McKelvey points out in Chapter 27. The type of mineral, that is, the relationship of molecules within the unit cell, is of special concern to the manufacturer of clay products, as well as to the geologist and engineer working upon construction, because of the variation in properties with respect to type of clay mineral. At times the geologist uses mineral composition as a means of tracing sedimentary strata from one drill hole to another (correlation problems), or as an index of the environmental conditions of deposition of the sediments. Physical properties of sediments are of special interest to manufacturers of abrasives, insulation materials, or aggregates for concrete.

The mass properties of sediments, such as density, resistivity, radioactivity, or compressibility, concern the geophysicist and geologist in prospecting for oil, as indicated by Beers in Chapter 4.

The processes that affect sediments concern all people who use sediments. The character of sediments and their response to stress depend on the processes that lead to the formation of the sediments. In addition, the processes themselves have certain very special applications, such as soil erosion, gullying of arable lands, degradation and aggradation of stream valleys below dams, silting in reservoirs, beach erosion, development of harbors and breakwaters, stream channel control, and silting in irrigation canals (Brown, 1948).

Lastly, sediments are of great use to the geologist interested in determining the mode of origin of sediments, or the environmental conditions under which they were deposited. For, if the geologist knows the mode of origin and if he understands the distribution of sediments and their attributes in the environment of deposition, he is in a position to predict what the nature of the sediments will be at some place beneath the surface of the ground. Using information obtained from sediments exposed in some outcrop or drill hole, the geologist is constantly being called on to indicate the nature of the sediments at some distance from these exposed points. If the geologist cannot predict, he has to guess. Hence he should endeavor to learn all he can about sediments, so that he can foretell, with desired reliability, the nature of the deposits in the unexposed places. Geologists have a long way to go in this respect, but the goal is clear. It is hoped that this chapter will help some people along toward that goal.

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CHAPTER 2

ORIGIN OF SOILS

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WHAT IS SOIL?

To the geologist and the engineer Ramann's definition of soil appears familiar: "The soil is the upper weathering layer of the solid earth crust." However, Ramann's definition fails to stress the concept of the *soil profile.* Contrary to common belief, soil is not a randomized aggregate of inorganic and organic particles. Soil is a body possessing definite organization. Soil has vectorial properties. Along an imaginary line extending from the surface of the soil toward the center of the earth (z-axis), the sequence of soil properties differs profoundly from that along lines parallel to the surface. Soils have a profile.

Profile characteristics of soils may be conveniently displayed by *soil property-depth functions* as illustrated in Fig. 1. The zones of maxima and minima are designated as horizons. The surface soil, which has lost material to the lower strata, is labeled A horizon (A_1, A_2), whereas the lower soil stratum, which has gained substances, is denoted B horizon (B_1, B_2). The zone underlying the B horizons is called C horizon (C_1, C_2). It may correspond to the original rock or parent material.

FACTORS IN SOIL FORMATION

On the earth as a whole, there are millions of different soils or, more specifically, different soil profiles. Yet, in spite of an apparent hit-and-miss pattern of soil distribution, a certain regularity in the occurrence of soils is discernible. It is of two kinds. First, similar types of soils are found in various regions. Thus the podsol profile (Fig. 1) occurs in Sweden, in Russia, in Germany, in the Alps, in New England, in Canada, in California, in equatorial South America, and in many other parts of the world. Second, dissimilar soils may be grouped into sequences such that the properties of the soils within a sequence vary in a systematic manner.

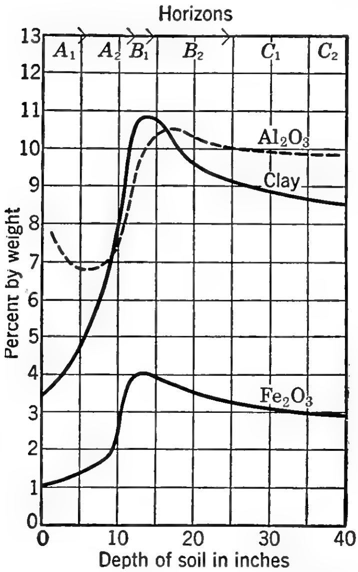


FIG. **1.** Variation of soil properties with depth of soil (podsol profile).

The genetic and geographic relationships among soils may be conveniently expressed as

$$s = f(cl, o, r, p, t) \qquad (1)$$

The letter s denotes any soil property such as color, reaction (pH), clay content, nitrogen content, or lime. The symbol f designates "function of," or "dependent on." The letters in parentheses represent the soil-forming factors. The specific symbols have the following significance:

cl = air climate (environmental climate)
o = species of organisms, that is, flora and fauna
r = topography, including certain hydrologic features
p = parent material, defined as the state of the soil at the soil formation time zero
t = time of soil formation (age of soil)

Equation (1) is employed in two ways. First, in a qualitative sense, as a shorthand notation for stating that soils are affected by climate, organisms, topography, parent material, and time. The second mode of interpretation treats the soil-forming factors as independent variables, which define the state of the soil system. This approach permits studying functions of individual soil-forming factors, as follows:

Time functions or chronofunctions:

$$s = f(t)_{cl,o,r,p}$$

Soil properties are related to time (age of soil) under conditions of constancy of cl, o, r, p.

Parent material functions or lithofunctions:

$$s = f(p)_{cl,o,r,t}$$

Soil properties are related to parent material under conditions of constancy of *cl*, *o*, *r*, *t*.

Topography functions or topofunctions:

$$s = f(r)_{cl,o,p,t}$$

Soil properties are correlated with topographic and drainage features when *cl*, *o*, *p*, *t* are constant.

Climatic functions or climofunctions:

$$s = f(cl)_{o,r,p,t}$$

Soil properties are related to climatic variables under conditions of constancy of *o*, *r*, *p*, *t*.

Organism functions or biofunctions:

$$s = f(o)_{cl,r,p,t}$$

Soil properties are dependent on organic species. These functions deal with relationships between soil properties and organisms when *cl*, *r*, *p*, *t* are held constant.

The soil-forming factors *cl*, *o*, *r*, *p* are multiple factors and yield groups of functions.

Soils have many properties: s_1, s_2, s_3, s_4, etc. All properties taken together constitute a collection, assemblage, or ensemble of properties which is the soil. If the ensemble of *s* values is designated by the symbol $E_{(s)}$,

$$\text{Soil} = E_{(s)} = f(cl, o, r, p, t) \tag{2}$$

Just as each individual *s* property is a function of the soil-forming factors, so is the entire ensemble dependent on *cl*, *o*, *r*, *p*, and *t*. In practice, the variations of the ensemble are recognized as profiles, soil types, soil series. In accordance with the five pedologic functions, the ensembles may be arranged in five sequences: chrono-, litho-, topo-, climo-, and bio-sequences. In contrast to equation (1), equation (2) is qualitative since "soil" cannot be assigned a single numerical value.

TIME (CHRONOFUNCTIONS AND CHRONOSEQUENCES)

The rate of soil formation varies widely. It is often stated that it takes thousands of years to produce one inch of soil. As judged from weathering of dated buildings and tombstones, this estimate is probably correct provided that very resistant rocks such as granite, porphyry, quartzite are considered. Softer rocks, like certain sandstones and shales, weather much more rapidly. In unconsolidated materials such as loess, sand dunes, moraines, alluvial deposits, and volcanic ash layers, visible profile development may take place in a few centuries or even decades.

Examples of the chronofunction

$$s = f(\text{time})_{cl,o,r,p}$$

are given in Fig. 2 for the s-property calcium carbonate ($CaCO_3$). The curves refer to the leaching of $CaCO_3$ from the surface layer of English

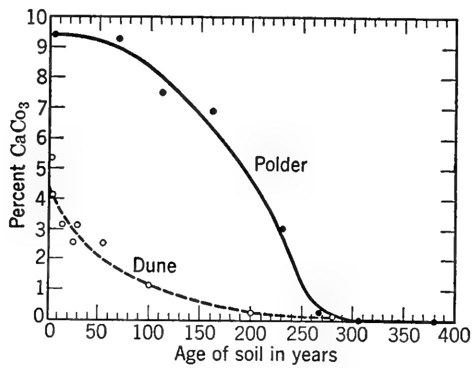


FIG. 2. Time functions of leaching of calcium carbonate in English sand dunes (Salisbury) and Dutch clay polders (Hissink).

sand dunes and Dutch clay polders (Jenny, 1946). In the cool, humid climates of England and Holland, about 300 years are required to free the surface soil of lime.

An example of a chronosequence of depth functions

$$E_{(s)} = f(\text{time})_{cl,o,r,p}$$

is presented in Fig. 3. The three soils Yolo, Zamora, and Hillgate were formed on alluvial material derived from sedimentary rocks, in a climate having mild, humid winters and hot and dry summers (California). The vegetation is grass. The relative age of these soils is inferred from the physiographic positions of the alluvial fans and terraces. Yolo is the youngest soil; Hillgate the oldest. It may be noticed that the density of the subsoil (B horizon) increases as the soils become older.

Examination of numerous time functions indicates that the soil properties s have rates of change with time, ds/dt which become smaller as the age of the soil increases. Soils which have become relatively stabilized in relation to time are often designated as *mature soils.* Soil maturity does not imply complete arrest of soil development; it merely indicates relatively slow reaction rates. In climates which are not extremely dry (deserts) or cold (arctics), mature soils have well-developed profile features. The time necessary to develop

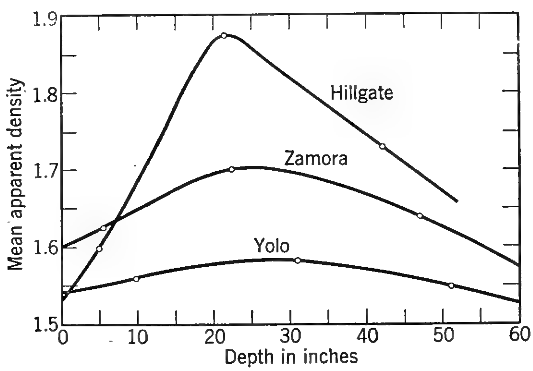


FIG. 3. Chronosequences of soil profiles (Harradine). The age of the soil increases as follows: Yolo < Zamora < Hillgate.

mature soils varies with the constellation of the soil-forming factors. In soft, porous, parent materials stabilized humus profiles may evolve within a few centuries. To produce claypan soils, which have B horizons rich in clay, probably tens of thousands of years are required.

Soils are sometimes studied in accordance with the equation

$$E_{(s)} = f(\text{time}) \tag{3}$$

Here the subscripts are missing. The soil-forming factors are not kept constant. This formulation represents the *historic approach.* Soils are studied in relation to time, irrespective of time changes of climate, and the biotic factor. The historic approach is sometimes designated as the study of *soil evolution,* as it may occur during cycles involving long geological periods. In contrast, the chronofunctions deal only with those soil changes which take place under relatively constant cl, o, r, and p.

PARENT MATERIAL (LITHOFUNCTIONS AND LITHOSEQUENCES)

In the time functions in Fig. 2, the left end of each curve shows the value of the soil property $CaCO_3$ at the beginning of soil formation. The soil at zero time is designated as *parent material*. It may represent consolidated or unconsolidated rock in the broadest sense of the word.

Contrasting soil formation on granitic rocks with soil formation on basaltic rocks has little pedologic significance unless the magnitudes of the remaining soil-forming factors are indicated. Theoretically, the role of different parent materials in soil formation can be assessed only if cl, o, r, t are either constant or ineffective.

An illustration of a parent material function or lithofunction is given in Table 1. It refers to soils derived from Winona glacial till in north-

TABLE 1

LITHOFUNCTIONS OF GLACIAL SOILS IN ILLINOIS

(Kellogg *et al.*, 1949)

Type of Soil	Composition of Parent Material (Till)		Properties of Soil	
	Clay	$CaCO_3$	Clay content of *B* horizon	Depth of leaching of carbonates
	%	%	%	inches
Saybrook	<25	27.8	<38	36.1
Elliot	25–35	28.2	38–46	32.0
Swygert	35–44	24.1	46–53	28.8
Clarence	>44	20.6	>53	25.9

eastern Illinois. It is proper to assume that cl, o, r, t are the same for all profiles. The higher the clay content of the till, the higher is the amount of clay in the *B* horizon of the derived soil. The Winona glacial tills also vary in their content of calcium carbonate ($CaCO_3$). During soil formation, calcium carbonate is leached from the surface into lower strata. The depth of leaching is controlled by the clay content of the till. Its influence overshadows the inverse relationship of the carbonate content of the till.

In humid, temperate, and cool climates, soils formed from granite are frequently coarse-textured and acid, and they often have a superficial humus layer of the mor type. Under similar climatic conditions, soils derived from diorite and the most basic gabbros are usually deeper and better supplied with calcium and phosphorus. They have mull types of humus layers (Kellogg *et al.*, 1949).

Owing to the interplay of soil-forming factors, the systems of soil classification based upon geologic features lack generality. They may

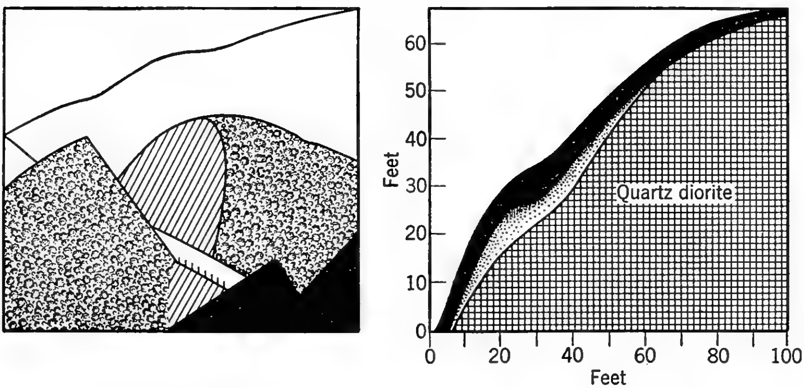


Fig. 4. A slope sequence. Left: sketch showing deep road cuts through chaparral-covered hills of "soft" quartz diorite. Right: exposed soil mantle illustrating depth of soil in relation to slope.

be valuable in regions of relatively uniform climate and constancy of other soil-forming factors. If comparisons of soils of entire continents are attempted, the geologic systems do not portray the soil relationships correctly.

Topography (Topofunctions and Toposequences)

The topography or relief factor is complex, for it includes, in addition to degree of slope, length of slope, shape of slope, and exposure, certain hydrologic features commonly referred to as drainage.

A pure slope sequence, in absence of ground-water influences, is depicted schematically in Fig. 4. On soft quartz diorite, south of San Francisco, California, the dark soil mantle varies in thickness in relation to slope features. These variations in soil depth are the result of erosion, soil creep, seepage, etc., all being functions of slope.

Slope sequences become especially marked when capillary rise from ground-water tables influences the soil profile. In humid regions, temporary or permanent ground-water influences produce peat and bog conditions. In arid regions, alkali soils and saline soils may result. Figure 5 illustrates such a hydrosequence in the semi-arid Coalinga area of California. On an expansive, gently sloping, colluvial fan, consisting of outwash from softly consolidated calcareous sandstone and shales, all soil-forming factors—save one—are constant. This

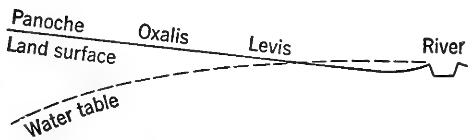


FIG. 5. Schematic illustration of a toposequence of soils influenced by ground water in arid California.

variable factor is represented by the plumb distance from the surface of the soil to the temporary water table which forms during the rainy season. As a result of capillary rise of the salty ground water, the uniform fan material became differentiated into Panoche soil, Oxalis soil, and Levis soil. The Panoche soil, lying on the upper portions of the fan, is nearly free of alkali. The wet end of this hydrologic sequence, represented by the Levis soil, is strongly impregnated with salt. The Oxalis soil, situated between the two extremes, possesses a nearly salt-free surface soil but has a slight to moderate salt content in the subsoil.

Combinations of slope and ground-water sequences are often classified as catenas (Bushnell, 1944).

CLIMATE (CLIMOFUNCTIONS AND CLIMOSEQUENCES)

Hilgard (1912) in this country and Dokuchaev in Russia showed that soils derived from the same parent material may have widely different properties, depending on the climate in which the soils are formed. Hilgard's comparison of chemical analyses of soils of arid and humid regions (Table 2) has become a classic. In general, soils from arid regions contain more acid-soluble materials than soils from humid regions. The differences are especially pronounced for Ca, Mg, K, and Na.

The fundamental difference in mode of formation of soils of arid and humid regions is conditioned by the moisture regime. In regions of low rainfall, water penetrates the soil to a limited depth only; weathering and soil formation do take place, but the products are not

TABLE 2

ANALYSIS OF SOILS FROM ARID AND HUMID REGIONS

(Hilgard, 1912)

Hydrochloric Acid Extracts

Region	No. of Analyses	Total Soluble Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
		%	%	%	%	%	%	%	%
Arid	573	30.84	6.71	7.21	5.47	1.43	1.27	0.67	0.35
Humid	696	15.83	4.04	3.66	3.88	0.13	0.29	0.21	0.14

removed from the profile. The soils remain neutral or slightly alkaline. The bulk of the water returns to the atmosphere by evaporation and transpiration, the latter mode predominating. Contrary to many beliefs, this water regime will not produce alkali or saline soils. As is discussed above, special ground-water conditions are necessary for their development.

Under high rainfall, water percolates through the soil profile and finally finds its way into rivers, lakes, and oceans. Soluble and dispersible substances are continuously removed from the soil. Soils in humid regions tend to become leached and acid.

With respect to the climate function, the complex factor *cl* may be conveniently split into a moisture variable m, and a temperature variable T, both being treated, mathematically, as varying independently of each other. Accordingly, one may speak of soil property-moisture functions and soil property-temperature functions:

$$s = f(m)_{T,o,r,p,t} \qquad s = f(T)_{m,o,r,p,t}$$

Good illustrations of s-m functions have been reported from the central portion of the Great Plains area, especially the states of Kansas and Nebraska. Here one may select localities having nearly identical mean annual temperatures but considerable variations in mean annual rainfall. Vegetation consists of grass communities; the parent material is loess and related wind-blown materials. By selecting samples from level ridges, topography also may be kept constant.

Figure 6, based on analyses by Alway (Jenny, 1941), portrays the variation of the calcium content of virgin soil profiles. As one proceeds from the semi-arid to the semi-humid zone, soil calcium declines in exponential fashion.

Figure 7 shows the trend of total soil nitrogen along the 11° C. an-

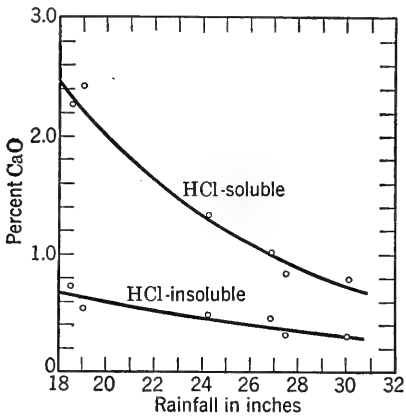


FIG. 6. Variation of calcium content of soil with rainfall in Nebraska. The total CaO content is the sum of the acid-soluble and acid-insoluble CaO content.

nual isotherm which lies slightly south of Alway's regions. Each dot represents the total nitrogen content of a soil sample taken to a depth of 10 inches. As mean annual rainfall increases, soil nitrogen also increases. Since soil nitrogen and organic carbon are closely related,

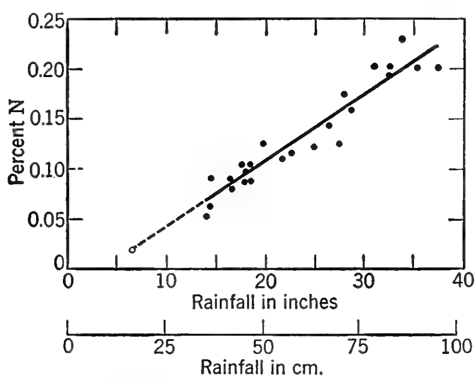


FIG. 7. Increase in soil nitrogen (and organic matter) with increasing mean annual rainfall in the Great Plains area.

the curve also indicates the trend of soil humus. Multiplying the nitrogen percentage by 20 gives the approximate humus percentage of the soils in this region.

Whereas the declining content of calcium must be interpreted as a result of leaching, the increasing nitrogen content must be attributed to the greater production of vegetation organic matter, especially roots, as a consequence of increased precipitation.

The Great Plains area also lends itself to the evaluation of *s*-*T* functions. Figure 8 shows the decrease of the total nitrogen content of the surface soils with increasing annual temperature. The samples

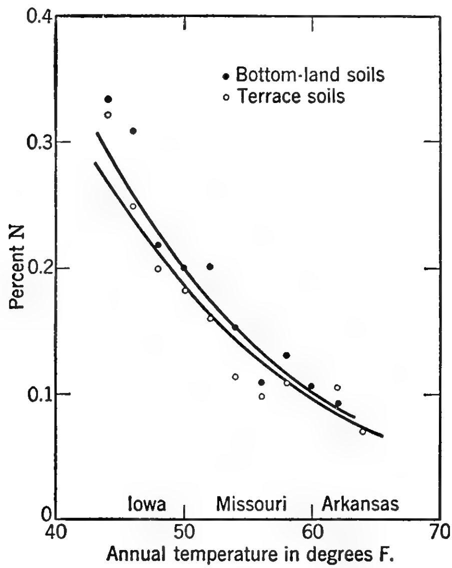


FIG. 8. Soil nitrogen (and organic matter) temperature relationships in the central United States.

were collected along a transect having fairly uniform annual moisture conditions and extending from Canada to the Gulf of Mexico.

In the Appalachian mountain chain of the eastern United States, relationships between average clay content of soils (to a depth of 40 inches) and latitude (or annual temperature) have been reported (Jenny, 1941). Figure 9 illustrates the increase in soil clay with rising annual temperatures for soils derived from basic igneous rocks, mainly diorite and gabbro. This transect extends from southern New Jersey to Georgia. The annual rainfall varies from about 40 to 50 inches. Each dot represents one soil profile.

Not only does the amount of clay vary with temperature, but so does the chemical composition of the clay. In the northern portion of the above-mentioned belt, the silica-alumina ratio of the soil clay is greater than 2.0; in the southern portion it is considerably below 2.0.

A few decades ago the reaction against geologic concepts in soil formation was extreme, and many attempts were made to classify soils solely according to climate. Although such systems have many attractive features, the oversimplification leads to gross misrepresentations. The interplay of all soil-forming factors cannot be ignored.

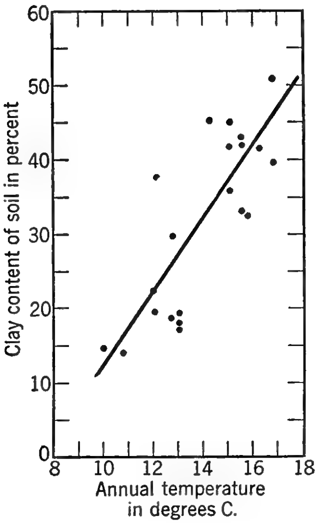


FIG. 9. The average clay content of soils derived from basic igneous rock increases from north to south (eastern United States).

BIOTIC FACTOR (BIOFUNCTIONS AND BIOSEQUENCES)

In soil investigations, the biotic factor is usually restricted to aspects of vegetation. The vegetational factor refers to kinds of species of plants (flora) and not to the abundance and yields of plants. The latter aspect is a dependent variable, being itself conditioned by soil and environment.

In nature it is difficult to evaluate the role of vegetation on soil formation. It is necessary to locate soils which carry different kinds of plants, but which, at the same time, have identical conditions of climate, parent material, topography, and time. An extensive region which satisfies these conditions is found in the Middle West, more specifically, the prairie-timber transition zone. Accurate comparison of prairie and forest soils shows that forests tend to accelerate soil formation. The soils are more acid, lime is leached to greater depth, and translocation of clay is enhanced.

PROCESSES OF SOIL FORMATION

The functional relationships between soil properties and soil-forming factors hitherto discussed are formalistic in nature. They record observed dependencies among variables. They are not concerned with mechanisms of soil formation, and they are not based on physical, chemical, or biological theories.

In contrast, the elucidation of processes of soil formation requires the application of knowledge and concepts developed by the basic sciences.

Nitrogen and Organic Matter in Profiles

Soluble nitrogen compounds in the rain water increase the nitrogen content of the soils to the extent of a few pounds of nitrogen per acre per year. More important is the fixation of atmospheric nitrogen by soil bacteria, living either non-symbiotically (Azotobacter group and Clostridium group), or symbiotically in association with legumes (nodule bacteria). The contribution of biological fixation of atmospheric nitrogen may amount to a hundred pounds or more of nitrogen per acre per year.

The total amount of nitrogen and organic matter * in soils assumes substantial magnitudes (see Table 3). Its rate of accumulation is

TABLE 3

Total Amounts of Nitrogen and Organic Matter in Selected Profiles

Type of Soil	Depth of Profiles	Nitrogen	Organic Matter
	inches	lb. per acre	lb. per acre
Grassland soil			
Cultivated (Yolo soil, California)	60	10,700	180,400
Pastured (Cayucos soil, California)	36	8,880	147,000
Forest soil			
Under oak (Shaver Lake, California)	50	5,650	104,000
Under pine (Shaver Lake, California)	50	5,800	154,500
Tropical forest soil			
(Chinchiná, Colombia, S. A.)	50	31,400	404,000
Soil from tropical rain forest			
(Calima, Colombia, S. A.)	30	22,400	328,000

conditioned by the rate of addition of organic matter by vegetation and by the rate of decomposition by soil microorganisms. Under conditions of relatively constant vegetation, a quasi equilibrium of soil organic matter is reached in a few centuries. The annual rate of decomposition is then nearly equal to the annual addition of vegetative material. It is estimated that annual decomposition rates of soil or-

* Humus represents the dark fraction of organic matter (Waksman, 1938). It consists of compounds synthesized by microorganisms from dead plant remains. As there is no standardized method of determining humus, soil scientists prefer to report total organic matter, obtained by multiplying organic carbon by the factor 1.742.

ganic matter amount to a few percent. In other words, in a stabilized organic matter profile annually 1 to 2 percent of the soil organic matter is lost and, *eo ipso,* replenished by decay of organisms.

In grassland soils the bulk of soil organic matter is derived from the decomposition of the root system. In forest soils a considerable portion may be acquired by infiltration of humus from decomposing leaf layers lying on top of the mineral soil.

PEDOCALS AND THE FORMATION OF LIME HORIZONS

Many soils in arid and semi-arid regions are characterized by lime horizons. Throughout the profile there are seams and nests of lime concretions, the individual concretions varying in size from pinheads to pea and nut size. The number of concretions per unit soil mass is greatest in the subsoil (lime horizon). Chemical analyses of such soil profiles reveal a high CaO content of the soil in the lime horizon and relatively low contents in the horizons above and below. Such soils were designated by Marbut as pedocals.

If a uniform parent material containing some calcium carbonate is assumed, the formation of the lime horizon may be visualized as the consequence of calcium carbonate-bicarbonate equilibria which are regulated by the carbon dioxide pressure of soil air.

Root respiration and decay of vegetable matter which are very active in the surface soil produce large amounts of carbon dioxide. It converts the relatively insoluble calcium carbonate to the much more soluble calcium bicarbonate. Percolating rain water translocates the bicarbonates from the surface soil to the subsoil. There, owing to reduced CO_2 pressure of the soil air, which is the result of a low biological activity, calcium carbonate is precipitated as lime concretions. In areas of low annual rainfall the carbonate horizon is close to the surface. As annual rainfall increases, the lime horizon moves to greater depth and, finally, above 40 inches of rainfall—in the temperate region—completely disappears from the soil profile.

On uplands and high terraces, lime horizons will develop only if the parent material is high in bases. Thus, in semi-arid California, soils derived from basic igneous rocks frequently possess calcareous subsoils; but soils derived from acid igneous rocks (for example, granite) rarely do. Likewise, non-calcareous sandstones do not produce calcareous profiles. In these soils Ca exists as Ca-clay rather than $CaCO_3$.

On the other hand, soils of arid regions which are under the influence of ground water usually contain carbonates regardless of the nature of the parent material.

WEATHERING AND CLAY FORMATION

Many of the common soil-forming minerals, such as feldspars, micas, pyroxenes, consist of chains and networks of tetrahedra and octahedra whose corners are occupied by $O^{=}$ and OH^{-} ions. The small interstices in the centers of the tetrahedra are occupied by Si^{++++} or Al^{+++} ions. Inside the octahedra are located Al^{+++}, Mg^{++}, Fe^{+++}, and Fe^{++} ions. These negatively charged oxygen and hydroxyl polyhedra share corners and edges, and they are balanced and held together by positive cations, especially K^{+}, Na^{+}, Ca^{++}, Mg^{++}.

Whereas the interior of any crystal is in electrical equilibrium (Pauling's rules), the surfaces of many crystals are composed of ions whose valences are not completely satisfied. For an orthoclase crystal, which consists of joined Si- and Al-tetrahedra and K ions in intertetrahedral cavities, the surface may be schematically depicted as in Fig. 10 (left side).

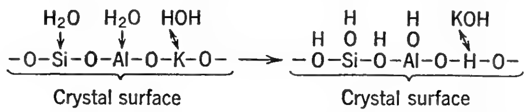


FIG. 10. Schematic presentation of orthoclase surface reacting with water. Hydration of oxygen ions not shown.

Upon the addition of water two reactions may occur. First, *hydration,* whereby water molecules (dipoles) are attracted to the unsatisfied valences of exposed Si and Al ions. The polarization of the attracted water molecules may become so strong that some of the H ions are expelled. They may become attached to exposed O ions which are thus converted to OH ions. The exposed polarizing Si and Al ions become surrounded by OH ions (water molecules minus H).

The second reaction, proceeding simultaneously and independently of hydration, consists of an ion exchange (hydrolysis) between exposed K ions of the lattice and H ions of water, as follows:

$$\boxed{\text{Orthoclase}}\ K^{+} + H^{+}OH^{-} \rightleftharpoons \boxed{\text{Orthoclase}}\ H^{+} + K^{+}OH^{-}$$

The liquid phase acquires alkalinity (pH 9–11), and the crystal surface gains H ions, which tend to combine with $O^{=}$ to form OH^{-}.

As a result of hydration and hydrolysis, the exposed oxygen tetrahedra become partial hydroxyl tetrahedra. Aluminum tends to attract further OH ions to assume its preferred octahedral configuration of hydroxyl ions. Coupled with the absence of stabilizing intertetrahedral K ions, the surface layer becomes unstable and polyhedra peel off.

Tetra- and octahedra liberated from feldspars and other minerals aggregate among themselves to form clusters of colloidal size, namely, colloidal silica, colloidal aluminum hydroxide, and mixtures, the colloidal alumino-silicates. Although young colloidal particles are probably amorphous, upon aging the polyhedra orient themselves to definite crystal lattices such as cristobalite, diaspore, bauxite, goethite, gibbsite (hydrargillite), clay minerals of the montmorillonite-beidellite-nontronite group, clay minerals of the hydrous mica-illite-vermiculite group, and clay minerals of the kaolinite-halloysite group. (Compare Chapter 25.) Fe ions of the original minerals tend to be excluded from incorporation into clay particles. They form the stable oxyhydroxides, such as limonite, goethite, and hematite.

It does not appear necessary that primary minerals undergo complete breakdown into individual polyhedra. Fragments of chains and sheets of tetra- and octahedra may recombine. Sometimes mere ionic substitutions bring about fundamental alterations, such as the conversion of biotite into vermiculite.

The specific conditions which control the formation of the various clay minerals in soils are not well known. Long ago Mattson showed that the $SiO_2:Al_2O_3$ ratio of colloidal alumino-silicates is influenced by the *p*H of the medium in which they are formed. As the reaction changes from alkaline to acid, the ratio increases. In general, as stated by Ross and Hendricks (1945), "Alkaline feldspars and the micas tend to alter to kaolin minerals, whereas ferromagnesian minerals, calcic feldspars, and volcanic glasses commonly alter to members of the montmorillonite group." The roles played by climate, time of weathering, vegetation, and drainage conditions have not yet been elucidated.

FORMATION OF CLAYPAN SOILS AND THE MIGRATION OF COLLOIDAL CLAY PARTICLES

Numerous soils exhibit accumulation of colloidal clay particles in the *B* horizon (Fig. 1). Extreme cases of clay accumulation produce soils known as claypan soils. Their *B* horizons may be so tight and sticky that they are nearly impermeable to water and air.

The source of clay in the *B* horizon is twofold. First, clay is formed in place as a result of weathering. It is possible that the subsoil region is especially conducive to clay formation, owing to favorable moisture conditions. Second, clay accumulates in the subsoil as a result of downward migration of colloidal clay particles from the surface soil.

The downward migration of clay is governed by colloid chemical principles, especially dispersion and flocculation. Colloidal clays such as montmorillonite clays tend to form stable suspensions, provided that free electrolytes (salts, acids, bases) are absent. Such clays are said to be highly dispersed. Their particle sizes are very small—of the order of a few hundred Ångstrom units (1 Ångstrom unit = 10^{-8} centimeters).

Addition of suitable amounts of electrolytes to dispersed clay systems will produce flocculation. When observed under the ultramicroscope, it is seen that the tiny individual clay particles unite to form aggregates or flocks which may become so large that they settle readily under the influence of gravity. The flocculation of clays by mono- and divalent cations is usually reversible. Removal of excess electrolyte will restore the system to its dispersed state.

The phenomenon of protective action of humus also must be taken into consideration. Leaching a soil with dilute ammonium hydroxide yields a dark-brown extract which contains colloidal humus particles. This humus extract possesses the power of protective action. If a small amount of colloidal humus extract is added to a dispersed clay system, its flocculation value becomes higher. In other words, a higher amount of electrolyte must be added to produce clay flocculation. Conversely, the addition of colloidal humus to a flocculated clay often results in dispersion of clay. The clay aggregates separate into the ultimate clay particles.

These aspects of colloidal chemistry aid in the understanding of clay migration. Let us postulate a uniform parent material of medium texture containing, say, 10 to 20 percent of clay, and 5 to 10 percent of calcium carbonate. Loess and many alluvial deposits closely correspond to such a hypothetical parent material. The climate is assumed to be humid.

Owing to the presence of calcium carbonate and bicarbonate, the clay exists in the flocculated form. It is in a state of rest. As calcium bicarbonate is being leached downward, the surface soil's electrolyte concentration is reduced below the flocculation value of the clay. Aided by the protective action of soil humus, the clay aggregates begin to disperse. The fine individual particles are carried by the percolating water to the subsoil.

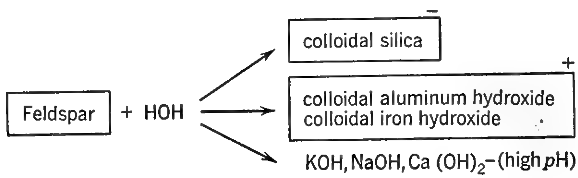
In the lower part of the subsoil, the high electrolyte concentration reflocculates the clay particles. As colloids settle out, the zone of illuviation becomes denser, the pores smaller, and additional migrating clay particles may be retained by mere sieve action, even in absence of excess electrolyte. The surface soil becomes depleted of clay, and the accumulation zone (*B* horizon) becomes thicker. The resulting extremely slow passage of water preserves the claypan over very long periods of time.

Lateritic Soils and Laterization

More than 100 years ago, in 1830, Buchanan described the red soils of India which are used locally for making bricks ("later"). In ensuing years the word "laterite" was applied to all red soils occurring in tropical regions; in fact, sometimes to all red soils anywhere. In recent years, especially under the influence of Pendleton, the concept of laterite has tended to be restricted to specific soil strata rich in sesquioxides, possibly formed under the influence of ground-water conditions.

The literature on laterites and lateritic soils is very voluminous. Among pedologists the prevailing viewpoint stresses laterization as a widespread soil-forming process of humid regions in which silica and bases are lost from the soil profile. However, only in extreme cases would laterization produce an actual laterite as defined by Buchanan and Pendleton.

According to Wiegner (1926), laterization is the direct result of normal weathering of rocks in absence of acid humus. In accordance with the ideas on rock decay presented in a previous section, one may write schematically



Since colloidal silica is negatively charged, alkaline reaction produced by the free bases will disperse it, and silica will leave the soil profile. Often silica is found precipitated in lower soil strata as chalcedony.

Iron and aluminum hydroxides form positively charged colloids, and they are flocculated at high pH. Accordingly, the sesquioxides remain in the soil. The preferential leaching of silica tends to limit the formation of clays to those having narrow silica-alumina ratios. Accordingly, laterization is characterized by preferential accumulation of sesquioxides and -hydroxides (gibbsite, limonite) and kaolinitic clays. Soil colloids extracted from lateritic soils have silica-alumina ratios of 2 and less, as illustrated in Fig. 11.

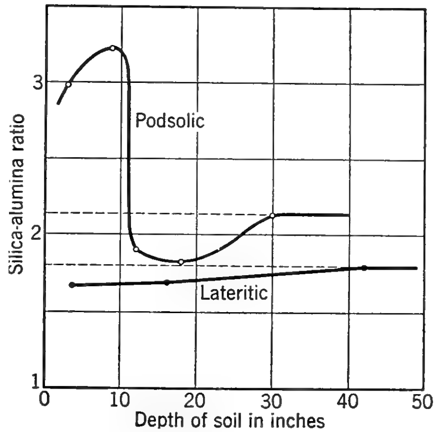


FIG. 11. Illustration of lateritic and podsolic weathering and soil formation. Silica-alumina ratios of clay colloids isolated from various soil horizons.

According to Wiegner, laterization takes place, on a minute scale, in frigid zones, above the zone of vegetative growth. Its prevalence in tropical regions may be the result of a combination of warm humid climate, which favors hydrolysis and leaching, and length of weathering periods embracing the entire Pleistocene and a considerable part of the Tertiary. Laterization should be especially prevalent in deep horizons where infiltration of humic acids is negligible.

PODSOLS AND PODSOLIZATION

The podsol profile (Fig. 1) occurs under a great variety of environmental conditions in cold, temperate, and tropical regions. It consists of the following horizons:

A_0: <1 to 5 inches. Partially decomposed forest litter and leaf mold.
A_1: 1 to 6 inches thick. Dark brown humus layer (raw humus) mixed with mineral soil; strongly acidic (*p*H 4).
A_2: 1 to 8 inches thick. Bleached horizon, grayish white; relatively rich in silica.
B_1, B_2: 2 to 15 inches thick. Rust-brown horizon with accumulations of iron hydroxide and some humus; also known as ortstein.
C: parent material, usually of sandy or loamy texture.

The characteristic chemical feature of the podsol profile is displayed by the trend of the silica-alumina ratio of the colloidal clay fraction isolated from various horizons (Fig. 11). The curve reaches a maximum in the A_2 horizon and a minimum in the B horizon.

To comprehend the formation of a podsol profile, or, in other words, the process of podsolization, we may resort to ideas expressed by Wiegner (1926). He stresses the role played by the acid humus colloids in bringing about the reversal of the process of laterization.

Wiegner reasons as follows: From the thick organic A_0 and A_1 horizons, acid humus colloids enter the mineral soil and neutralize the bases as rapidly as they are being formed. This important step shifts the weathering process from lateritic to podsolic. The soil solution, being acid, flocculates negative colloidal silica, which thus remains in the surface soil. Acidity disperses positive colloidal aluminum and iron hydroxides, a process which is encouraged by the protective action of the acid humus colloids. Accordingly, colloidal iron and alumina are removed from the surface soil. They are reprecipitated in the subsoil (*B* horizon) where electrolyte concentration and *p*H are relatively high.

In contrast to mere clay migration, as it occurs in claypan soils, podsolization involves a differential behavior of colloidal silica and colloidal sesquioxides. Colloids extracted from A_2 horizons have high silica-alumina ratios. Those in the *B* horizon have low ones (Fig. 11).

Podsol formation postulates the presence of acid colloidal humus. Accordingly, it can occur wherever large amounts of acid humus are formed, be it as a result of low temperature, as in northern regions, or as a result of high rainfall, as in certain parts of the tropics.

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Chapter 3

THE LAWS OF SEDIMENT TRANSPORTATION

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It appears basically impossible to separate the description of sediment transport from that of erosion and deposition of the same particles, since erosion represents the initiation, and deposition the termination, of any sediment motion. However, if the term sediment transportation laws is used in the specific sense, that is, restricting the description of the relationships which link the rate of sediment motion at any flow section to the parameters of the flow and its boundaries, this separation is fully justified. It is in this sense that the transportation laws may be defined for the purpose of this chapter.

It has been shown in Chapter 1 in this symposium that sediment particles may differ in many respects, such as size, shape, specific gravity, roundness, mineralogical composition, to mention only a few. For the purpose of transportation studies, a knowledge of the size, settling velocity, and specific gravity of a grain is sufficient. Even at that, this may represent grain types which behave in three different manners.* The realization that each sediment mixture may contain all these different grains at any possible frequency makes it clear that a sediment mixture may be a very complex unit. It is not surprising that under these conditions sediment mixtures cannot always be treated as a unit, but that some part of a mixture may be moved in the same flow according to entirely different laws than is some other part.

* The terminology proposed by the American Geophysical Union (see *Transactions,* Vol. 28, Dec. 1947, p. 936) has been adopted in this chapter.

TYPES OF LOAD TRANSPORTED BY FLOWING WATER

In attempting to describe the various relationships between the sediment rate and the flow of the fluid which produces the transport of the material, it is always important to remember that every particle moving through a reach of a stream must satisfy two conditions: (1) It must have been eroded or otherwise have been made available in the watershed upstream from the reach. (2) It must have been moved down to the reach and through it by the flow. The rate at which each kind and size of particle is moving, therefore, is limited to its actual rate by either the first or the second condition. Needless to say, the laws derived from the two conditions restricting the rate of flow are inherently different. It has also proved to be helpful to introduce different terms for the two parts of the sediment load of a stream; thus that part of the load the rate of which is governed by its availability in the watershed is termed "wash load," and that part which is governed mostly by its ability to be moved in the stream channel is termed "bed-material load."

WASH LOAD

The rate at which the various sizes of the wash load of a stream are moving through a reach depends, according to definition, only on the rate with which these particles become available in the watershed and not on the ability of the flow to transport them. This may be interpreted to mean that, if the rate of flow is greater, more particles of given size can be transported if they are available. From this, again, one may conclude that wash-load particles are not deposited in the stream channels on their way from the place of erosion down to a point of measurement. They travel with the same velocity as the flow. The rate of transport of the wash load may be found to depend upon the different factors determining erosion, such as intensity of precipitation, rain-drop size, soil type, vegetal cover, and previous soil conditions, but not upon the discharge at the reference section, as has been shown by Vetter (1937). As these different parameters effecting erosion are very complex, and as the value of each parameter is not known for most of the larger watersheds, the rates of wash-load transport usually have not been analyzed in detail, but are given as an average annual load as determined from either lake surveys (Eakin, 1936) or suspended-load sampling programs.

As the supply of the wash load never reaches the capacity of the channel to transport it, it is never deposited in the main flow channel, and its rate, therefore, has no significance in determining the stability of the stream channel itself. As it represents usually a large part of the total load (90 percent in the Rhine River above Lake Constance), and as it is usually deposited at a lower volume-weight than the bed-material load (Iowa University, 1943), it is the most important part of any lake or reservoir deposit.

Several government agencies which are interested in the management of reservoirs, or in the rates of erosion, are today engaged in a very active program of sediment sampling. These agencies use suspended-load samplers for this purpose and thus sample the total load; thus some of the bed-material load may be included in estimates of the sediment load. All information so obtained is assembled by the Inter-Agency Committee on Sedimentation, which meets regularly in Washington, D. C., and which is responsible for the publication of the data. With this committee serving as a clearing house, duplication of effort within the government service is eliminated.

Some attempts have been made to map the sediment productivity of different areas in the country (Brown, 1945), but it is well known today that even the rate of wash load (measured in tons per year per square mile of drainage area) varies inversely with increasing size of the watershed area. The reason for this inverse relationship may be found in the deposition of wash-load material in overbank and dead-water areas.

Bed-Material Load

Basically the movement of bed-material load behaves differently from that of the wash load of a stream. In the past it has been furnished, and usually it still is being furnished, by the watershed at a rate that is higher than the capacity of the channel to transport the material. A certain percentage of this load has been and is still being deposited along the channel, reducing the actual transport down to the capacity load. If for any reason the sediment inflow into a given reach of a channel is smaller than the capacity load, the flow immediately scours some of the formerly deposited sediment from the bed and keeps the load constantly at capacity level. Bed-material load is thus always transported to capacity. For a given channel reach, the flow conditions usually can be described in terms of the stage or of the discharge. It must be expected, therefore, that the capacity to transport bed material can be given also in terms of the discharge. In this respect the relationship which gives the capacity of the stream to transport the various sediment sizes of the bed material at different flows is termed the "sediment function" (Fig. 1).

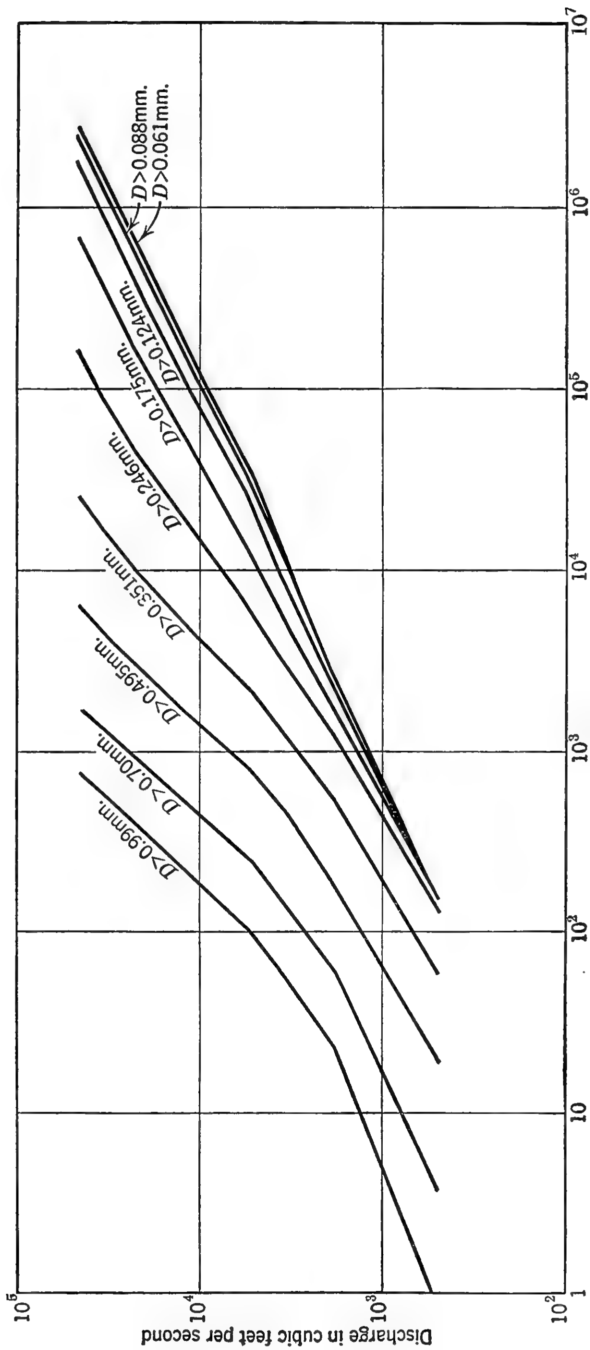

FIG. 1. Bed-load function, Rio Grande at Bernardo, New Mexico.

In an existing channel the sediment function may be determined experimentally. Instruments have been devised to measure that part of the bed-material load which moves along the bed as bed load or surface creep (Iowa University, 1940b); normal suspended-load sampling instruments and procedures (Iowa University, 1940a, 1948) may be used to measure that part of the bed material which moves suspended in the upper layers of the stream cross section. The total rate of these relatively large particles has been found to be actually a well-defined function of the discharge (Einstein, 1947), and this relationship may well be used to predict future or past bed-material motion in this same channel if the flow rates are known.

Whenever a reach of channel which has a sediment function, and which is usually called an alluvial reach, shows a low or zero rate of deposition or scour, the sediment function may be interpreted over a given length of time to determine the total or average bed-sediment supply of the watershed above. Basically, the sediment supply is naturally the primary factor determining the behavior of the stream, and in the course of centuries the stream channel has been built up by sediment deposits until it has finally become able to move the bed sediment at the rate of supply. The rate of transportation of load, therefore, may be used as an indicator of the sediment supply.

If the different types of bed sediment move in a given channel at rates which are a well-defined function of the discharge, it must be possible to determine this relationship analytically. Attempts in this direction date back to the last century, when the first bed-load equations were developed by DuBoys (1879). A bed-load equation, in contrast to what is termed a bed-load function herein, is a local relationship between the rate of sediment motion per unit of width and unit of time and the local bed and flow conditions. In such instances the bed usually is described by an average or representative grain size. The flow in any vertical section, both the average and the velocity distribution, is defined basically by the local shear stress and by the total water depth. In the usual cases of bed-material load, where most of the load moves near the bottom, the flow velocities may be derived from the local shear stress alone.

All the early bed-load formulas, and most of those that are used today, describe the flow by its shear stress only. In some of these formulas one or two coefficients have been introduced which may change in value somewhat for different depths and sediment sizes (Vanoni, 1947). Recent attempts to eliminate the necessity of using these variable coefficients have led to an interpretation whereby the bed-load equation is used only to express the motion of bed material as surface creep in a very narrow layer above the bed, whereas all the bed material moving in higher layers of flow is interpreted as suspended load.

The existing suspended load theory (Vanoni, 1946) permits calculation of the sediment concentration at any point throughout the depth of a given flow, provided that the concentration at only one point in the depth is known. It has been found that the surface creep in the narrow layer which it occupies near the bed defines such a reference concentration. Conditions are encountered, especially in large streams with comparatively fine bed sediment, where the sediment goes into suspension easily; hence the rate of suspended-load transportation is many times larger than that of surface creep of the same bed particles. In these cases the material moved by surface creep may be negligible in amount in itself, but it still retains its large significance as a valve or trigger controlling all suspended-load concentrations.

All bed-load equations that are in existence have been derived from flume measurements. Experimental flumes that have been used for this purpose have ranged from a few inches to 7 feet in width and depth and from 5 to 200 feet in length. Most equations were derived originally from experiments with uniform sediment and then checked for applicability to sediment mixtures. Most mixtures for which the range of particle sizes is not excessive and which do not contain a large percentage of particles finer than 0.2 millimeter have been found to move as a unit. This finding indicates that the mechanical composition of the bed sediment is about the same as that of the material being transported. If very small rates of transport are included in the experiment, or if one of the two limitations given above is transgressed, a considerable segregation of the particles becomes apparent, and an overall appraisal of the total transport by means of a representative grain diameter is impossible.

Thus it appears to be possible that the normal bed-load equations can be applied to the different components of a bed if the basic assumption is made that every particle moves according to a law that includes its own availability, its ability to move, and the capacity of the flow to move it. It appears that this law does not depend to a large degree on the presence of other sediment particles. This same assumption of non-interference between sediment particles in motion is also one of the basic assumptions of the existing suspended-load theory (Vanoni, 1946). The composition of the bed, however, determines the bed roughness and, indirectly, the flow pattern. Publications on this type of bed-load equation may be expected to appear in the next few years.

PRACTICAL APPLICATION OF BED-LOAD EQUATIONS

After a bed-load equation has been developed from flume experiments, it is very important to determine its applicability to natural streams by making measurements in such streams. Such measurements of sediment load should combine bed-load measurements (Einstein, 1944) with a suspended-load-measuring program in order to determine the bed-load function of the stream. For a comparison it is necessary, therefore, to integrate the specific load as obtained from the bed-load equation over the entire cross section. The integration of the transport over the cross section may be made on a basis of either local or average specific load; that is, either the hydraulic conditions from which the load is calculated may be averaged and the load calculated from this average flow, or the load may be calculated locally and then integrated over the cross section. Both methods lead to practical difficulties and call for various assumptions to be made. At the present stage of development in the field of sediment transportation, it is not clear in which cases one or the other method will give the best results.

The predominant significance of wash load in the silting of most reservoirs has been mentioned. In very few cases would this problem justify the separate and detailed study of bed-material load. Its main significance appears in problems of stream-channel stability, for which it has been shown that the wash load has no influence. If a stream is depositing annually a certain amount of sediment in its channel bed, flood damage must be expected to develop. The usual question in such a problem is whether or not any countermeasures are economically feasible to prevent all or part of the flood damage. This problem may be approached by either of two methods or by a combination of them. The rate of sediment supply may be reduced by retaining the material at its point of origin or in sediment-retention basins; or the sediment capacity of the channel in question may be increased by channel rectification and elimination of unnecessary flow resistance (Einstein, 1944), or by a combination of the two methods.

ROUGHNESS

A discussion of the laws of sediment transportation would not be complete without some remarks about the roughness conditions along a movable bed. This friction will determine the relationship between stage and discharge in the river, and it will determine the average velocity and the velocity distribution. It has been found that, basically, this friction may be described by von Kármán's logarithmic equations, using the constants which Keulegan (1938) has derived from Nikuradse's experiments for the flow along rough walls. The roughness diameter k in these relationships is represented by the grain diameter in the case of sediment of uniform size. For sediment mixtures the diameter used in computing the roughness factor k is the diameter known to engineers as D_{65}. That is, 65 percent of the weight of the sediment is composed of particles smaller than D_{65} and 35 percent of particles larger than this diameter.

Additional flow resistance is caused by the ripples and bars of the sediment bed and by the irregularities of the channel. Both may be expressed in terms of the specific sediment rate. From flume studies where channel irregularities are practically eliminated, one can learn that the additional friction due to ripples and bars is small for the very lowest and for extremely high rates of sediment transport, reaching a maximum value at an intermediate rate where sediment bars are most commonly developed. In natural rivers not constricted by artificial banks, the reduction of the additional friction at low sediment rates is counteracted by channel irregularities such that the overall friction coefficient is highest at lowest flows. These relationships are not sufficiently understood yet but are just as important for the calculation of an alluvial river as is the bed-load equation itself.

The above discussion pertains primarily to the rate of sediment transportation. Another phase of the sediment problem that has been investigated extensively in the past is the critical condition controlling the commencement of movement of the bed material.

TRACTIVE FORCE

The most common conception of the mechanics of bed-load movement is that a dragging force is exerted on the bed of a stream by the flowing water. This force, termed the tractive force, is the dragging or entraining force exerted at the base of a prism of water of unit area of the bed and of height equal to the water depth sliding, under the influence of gravity, down an inclined plane having a given slope. Critical tractive force is that tractive force which creates "general movement" of the bed material. General movement, as commonly used in this sense, is that condition under which sand grains up to and including the largest size available are in motion. This critical condition for movement is related to the specific gravity of the bed material and to such mechanical properties as grain size, grain distribution, and grain form.

Numerous flume experiments have been conducted to obtain a relationship between these various factors at the point of general movement. Kramer (1935), one of the first to attempt to formulate a criterion for defining critical conditions, used experimental data from all available sources and developed a formula in terms of sand size and distribution. In later investigations at the U. S. Waterways Experiment Station (1935), Kramer's criteria and data were used and a modified formula was derived.

Still later Chang (1939) analyzed all available data and also presented a formula for the critical tractive force in terms of the mechanical properties of the material. Numerous experiments were conducted at the University of Iowa (Mavis, Ho, and Tu, 1935) to establish a relationship between a competent bottom velocity, corresponding to impending motion of the stream bed, and the size and specific gravity of the bed material. Somewhat later Mavis and Laushey (1949) reanalyzed the Iowa data and presented a new relationship between critical bottom velocity and size and specific weight of the material.

The practical purpose of relationships between critical conditions for movement and the sediment characteristics is to establish permissible velocities in the design of earth canals. Also, in many bed-load formulas the rate of transportation is expressed as a function of the difference between the tractive force and the critical tractive force of the material in the bed. Although the theory underlying this reasoning, namely, that the transportation is a function of the "residual tractive force," is perhaps correct, in the practical case the critical tractive force is relatively small compared to the total tractive force, and its inclusion in a bed-load formula becomes primarily one of academic interest.

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Chapter 4

GEOPHYSICAL PROBLEMS IN APPLIED SEDIMENTATION

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One approach to problems in applied sedimentation cuts across the lines of development of the geophysical sciences. In following this application it is important to avoid the many preconceptions and prejudices one encounters in approaching geophysics for the first time. Many problems in applied sedimentation will benefit by the use of geophysical methods, but there is great danger in assuming that geophysics will provide a perfect solution. The history of many phases of geophysical science has been repeated too often: first, a brilliant idea showing exceptional promise of success, without practical limitations; second, an extravagant program of application without adequate buttressing of the contributory sciences; third, the inevitable disappointment following the misguided application; and, finally, a wholesale condemnation of the method employed, perhaps of geophysics entirely.

It is difficult to understand why some applications of geophysics have been developed in a scientific manner to produce valuable results, whereas other equally important applications have followed the unhappy course outlined above. Some people become emotional about geophysics. Either they ride the crest with unbounded enthusiasm, or they sink to the depths of despair when confronted with failures. This pattern has been retraced altogether too often during the past three decades for it to be passed by without comment. It is hoped that these remarks may spare the reader from similar unprofitable experiences.

Geophysics is no panacea. It has purpose, scope, and limitations. It can be used to advantage for many problems, and the overall costs are usually favorable. Its successful use involves broad knowledge and experience in many sciences. Strictly speaking, there is no single department of geophysics. It transcends the boundaries of many sciences, such as physics, mathematics, engineering, economics, hydrology, oceanography, seismology, meteorology, geodesy, terrestrial magnetism and electricity, and practically all phases of geology. If one approaches a problem in geophysics without recognizing the breadth of this segment of human knowledge, it is highly improbable that a satisfactory solution will be obtained. Restricting one's point of view too severely has accounted for many of the failures of the past. It is only through the complete integration of all related fields that a completely satisfactory solution may be achieved.

One may ask: "How can one person cover such a broad field of knowledge?" The problem is not new. It is one which the geologists have cultivated, one which accounts for their success in many fields of endeavor. Their guiding principle was stated many years ago by T. C. Chamberlain * as the *principle of working hypotheses.* Under the philosophy of this idea the investigator pursues the problem with an open mind. He does not formulate a final solution until he has attacked the problem from many angles. In the design of a foundation, for example, he will first study the geologic setting, the structure and stratigraphy of bedrock. Then, from the viewpoints of sedimentation and soil mechanics, he will examine the soil and overburden, viewing them not only as structural materials to support the foundation. As a geologist he will recognize that the soil in his hand is a result of many active processes, resulting in the soil as it is today, and constantly changing its properties. At some future time it may not possess the same characteristics. The scientist will look for new facts and new processes which in the future may modify present conditions. These researches lead him into the fields of seismology and earthquakes, oceanography, geodesy, hydrology and meteorology, geology and sedimentation.

The illustration depicts the principle of multiple working hypotheses. From each independent point of view a preliminary estimate of pertinent factors is achieved. When all possible points of view have been examined, they are integrated into an evaluation of the relative importance of each separate element. When this integration is made, a new factor will be noted, namely, that the whole is greater than the sum of the parts. Herein lies the great power of this working principle. When several independent factors are correlated, new factors appear which are the result of the interrelation of two or more components. In communication networks this element is known as "coupling." It represents a measure of the mutual and reciprocal rela-

* T. C. Chamberlain, The methods of the earth-sciences, *Popular Science Monthly,* Vol. 66, pp. 66–75, Nov. 1904.

tionships existing among the various parameters. It is important to estimate the probable significance of these coupling factors, first, as they are independently established and, then, as they are arranged to show their several relationships.

The development of a final solution is a series of probability determinations. At each successive stage a closer approach to the end result is achieved. With the addition of each sample of new data and the interpretation and correlation thereof, relative priorities of each partial solution become established. The final solution expresses the order of probabilities which the respective solutions bear to one another. One solution may rank very high and be employed as the first working basis.

This method of attack will stand in sharp contrast to that employed by some engineers and scientific workers. In many fields it is established practice to formulate a single, explicit, unique solution. The possibility of other solutions is not admitted. In geophysical sciences the number of variables is so large that a single solution cannot be depended on. It is necessary to use the multiple-hypothesis method to be certain that nothing has been overlooked. Sometimes not even this method will cover the field.

OUTLINE OF GEOPHYSICAL METHODS

The broad nature of geophysics, as indicated above, requires one to approach the subject slowly. A division can be made into: (1) "pure science" geophysics; (2) exploration geophysics for petroleum and minerals; (3) engineering geophysics (including soil mechanics); (4) geophysical aids to geologic mapping, surface and subsurface; (5) development of ore deposits; (6) petroleum production—primary and secondary recovery; (7) military and naval problems.

The advantage of viewing all these areas of interest together is that principles, techniques, and instrumentation developed in one area may find useful applications in others. Borrowing of ideas is important because of the high cost of geophysical research and development. A reflection seismograph used for petroleum exploration may cost $100,000 in capital outlay and an operating charge of $600 per diem. If there is any operating principle, technique, or instrument which the petroleum industry has already developed it is expedient to adapt it to new problems. The cost of geophysical research and development for new problems of sedimentation may be prohibitive. The wisdom of employing expert consultants in study groups is indicated by these costs. The experts bring with them not only a working knowledge of scientific principles, but also an intimate acquaintance with the implementation thereof.

Geophysical methods require the collection of substantial amounts of field data. For this purpose specially designed equipment is used, operated by trained technicians and scientists. The task of gathering field data with this equipment is, in itself, a special skill. Not only is the quality of data better, but also the unit cost is lower when the data are gathered by competent field units. In many areas of applied geophysics competence is widespread, but, for the past ten years, there has not been enough personnel to meet the demands. If geophysical activities continue at the current rate, little improvement of this condition can be expected. If more geophysicists are required, it is necessary that more schools of geophysics be established. In addition to their formal education, geophysicists also require a comprehensive program of field training. Excepting the petroleum industry, no such program of training is in effect. For these reasons many problems in sedimentation which would benefit from the attention of experienced geophysicists are now being neglected.

The following discussion contains the principal topics covered by the cited divisions of geophysics. These divisions exist mainly in the published literature. For convenience of reference they are retained herein.

"PURE SCIENCE" GEOPHYSICS

SEISMOLOGY

The subject of seismology includes earthquakes, their cause and their effect; frequency and places of occurrence; the internal constitution of the earth; long-distance propagation of seismic waves; microseisms, their origin and propagation, their correlation with meteorology, and their use in storm forecasting.

Applications to sedimentation. Seismology has many practical applications: the design of quakeproof structures; soil mechanics and foundation problems; selection of sites for installations, buildings and public works in consideration of the structural properties of the ground; amplitudes of vibrations from natural and man-made sources; soil tests and test equipment.

GEOLOGY

Sediments are one of the three fundamental rock types, and they cover three-fourths of the surface of the land areas of the world. Sedimentation comprises the following subjects: the fundamental laws of sedimentation; the work of water, wind, and ice in removing, transporting, and depositing sediments; the natural history of sediments and sedimentary rocks; provenance studies, the source rocks of sediments; alteration of sediments by burial, compaction, chemical, thermal, physical and igneous metamorphism; the effects of wind, frost, heat, water, ice and chemical agencies; the sedimentation cycle; the evolution of soils; the geologic processes at work on soils; structural geology, mountain and continent building as factors in the evolution of sediments and soils.

Applications to sedimentation. Geophysical applications include problems of installations: dam site, highway and public works construction; water supply; the properties and usage of soils.

Hydrology

Water and its effects constitute the subject of hydrology. Topics considered are: principles of origin of ground and surface water; distribution and recovery of water; hydrometeorology; precipitation, distribution, and variations; surface evaporation and transpiration of water; the permeability of rocks and soils; snow surveys; transportation of sediments by running water; sedimentation in reservoirs, lakes, and ponds; the water content of soils.

Applications to sedimentation. Applications of hydrology include water-supply storage; ground water; hydroelectric projects; flood control; storm protection; land drainage; irrigation; runoff control; stream flow.

Oceanography

The ocean and its characteristics constitute the subject of oceanography. Topics included are: ocean waves, tides, currents, and swells; water levels: diurnal and secular variations; tsunamis and seismic waves; forecasting of breakers and surf; interactions by the ocean and the atmosphere; physical properties of sea water, sea-surface temperatures; beach composition and construction; ocean channels, their structure and alteration.

Meteorology

Meteorology covers the subjects of weather forecasting; climatology; hydrometeorology; mean annual precipitation rates, runoff, storm and flood forecasting; water levels and water supply; mean annual temperature distribution.

Applications to sedimentation. Meteorology is related to sedimentation in many ways: water project system operations; determination of maximum rainfall, flood crests, reservoir capacities, flood storage basins; hydroelectric developments; reservoir and dam construction projects, irrigation projects, land usage surveys.

REFERENCES TO LITERATURE

At the end of this chapter is a list of references which the reader may consult for further information on the foregoing subjects. There is a wealth of knowledge in the texts and periodical literature cited in these references, much of which is in suitable form for immediate utilization by engineers and scientists who are approaching problems in sedimentation without previous experience in the field.

EXPLORATION GEOPHYSICS (FOR PETROLEUM AND MINERALS)

The United States petroleum industry spent approximately $500,000,000 during 1948 in search of new deposits of oil and gas. At least one quarter of this amount was spent in scientific methods of exploration employing geology and geophysics. Most of the latter sum was spent on exploration geophysics through the activities of approximately six hundred field parties in the United States alone. It may be inferred, correctly, that the expenditure of sums of this order implies the existence of a high degree of scientific and technical competence. It is true that the expenditures provide a return in new discoveries of oil and gas equal in value to many times the exploration costs. The success of the petroleum industry during the past twenty-five years is ample testimony to the philosophy of multiple working hypotheses. Although most of the money is spent on exploration geophysics, the strategy of long-range campaigns embraces every imaginable point of view in petroleum geology.

The consequence of this great effort has been the development of an extremely high degree of scientific and technical skill in the pursuit of new discoveries. The success of an exploration program, when distributed over a sufficiently broad base, is now taken for granted. There is a direct relation between the amount of oil discovered and the funds applied to the task. It is true that the unit cost of discovery is constantly rising, but the law of diminishing returns is not yet too seriously felt. Exploration by scientific means is still profitable on a large scale.

The technical basis of petroleum exploration geophysics can be expressed briefly. Through many years of trial and error the industry has found that many physical properties of rocks are systematically distributed with reference to oil and gas. Four or five of these properties are significant enough to warrant serious prospecting techniques.

More than half the money spent for geophysics is devoted to the seismograph, an instrument which measures the travel time of sound waves into the earth and return. The principle is as simple as the echo returning from a sharp discontinuity: a brick wall, the side of a cliff, or the edge of a forest. The principle was first developed in echo depth sounding after the sinking of the steamship *Titanic* by an iceberg in 1913. Since then the echo principle has been developed in many fields, finally resulting in the evolution of radar.

In its application to oil finding, the seismograph employs miniature earthquakes set off by small explosions of dynamite just below the surface of the ground. Sound waves traveling through the earth are in part returned to the surface by sudden changes in sound velocity. The sequence of layered rocks commonly found in oil provinces makes an ideal setting for the return of a series of echoes. Each reflection is recorded on a moving film which can later be analyzed to identify the origin of a long series of echoes. The reflection seismograph makes echo determinations over a network of points spaced from a few hundred feet to one mile apart on the surface of the ground. At each of these points there results a sub-sea-level datum value of each of the reflection horizons which appear on the prospect under survey. The numerical datum values, under the guidance of a competent geologist, may be contoured to show the attitude at depth of one or more reflecting horizons. If a horizon is related to the occurrence of oil and gas in the form of a confining trap, this fact will be inferred by the geologist from the contours. He will then recommend the drilling of a well upon a favorable site to investigate the conditions of permeability and saturation in the objective horizon.

By established refinements in the reflection technique it is possible to achieve a quantity of subsurface data which are equivalent to drilling a well at each reflection point. An accurate structural picture can be obtained as well as valuable stratigraphic data. If lateral changes in sedimentation occur, they may often be inferred from the character of reflection records received along the transition zone. Full use of the resolving power of the reflection seismograph in this application is rarely employed, but if fine detail is required it is available at additional cost. There are a number of controls over the resolving power which enable one to delineate fine structure within the grosser features if the expense is warranted.

Among the refinements which the reflection seismograph may employ with advantage is the accurate determination of the velocity of sound through the sequence of beds. For this purpose a special seismic detector is lowered into a well drilled through the rock formations.

Small explosions at the surface are recorded by the well detector at various depths so that individual formation velocities can be determined. It will be found that the formation velocities offer valuable guidance to the identification of the beds, becoming, thereby, a velocity signature.

This property is used in the refraction seismic method which maps only the major velocity horizons. The method is useful in large-scale reconnaissance surveys where fine detail is not required. It is also adaptable to small-scale problems such as the measurement of the thickness of soil and overburden, the depth to bedrock, and the distribution of these quantities over sites for buildings and public works construction, highways, reservoirs and storage basins, and in the search for new supplies of ground water.

In seismology for petroleum exploration, the general principles of earthquake seismology are employed in a restricted degree. It is sufficient to note that the velocity of sound in rocks is the variable parameter upon which the success of the seismic methods depends. Their use is restricted to the delineation of structure and stratigraphy in rocks. If these factors are systematically related to the occurrence of oil and gas and of ore deposits, the method may achieve economically useful results. There is no implication that an accurate seismic survey directly indicates the occurrence of valuable treasure. This inference must be based upon other considerations, principally geological. The use of the seismograph is comparable with the use of the transit in surface surveying. Both collect numerical data which may be contoured to show relative relief over the area surveyed. Both methods are precision forms of engineering application, and as the indications of either are established by the presentation of numerical data, other realms of science become involved. It is outside the jurisdiction of the map maker to interpret the significance of the data listed thereon.

Other properties of rocks whose distribution may have bearing upon the occurrence of petroleum and minerals are specific gravity, magnetic susceptibility, electric conductivity, and radioactivity. By gathering data at the surface of the earth, or in bore holes drilled especially for the purpose, it is possible to infer something of the distribution of rocks beneath the surface from a map of the observed and reduced data.

Variations in subsurface rock densities reveal themselves at the surface by the distribution of contours of measured values of gravity. By making very precise measurements of gravity at a series of closely spaced points it is possible to derive significant indications of the distribution of rocks at depth. The method has a high resolving power when all possible corrections are made. These include corrections for sea-level elevation of each station, distribution of surface rock densities and their elevation, topographic corrections, and instrumental drift corrections. When properly gathered and interpreted, gravity data are of great value in detecting the presence of buried structures and mineral deposits. Interpretation of the data requires an intimate knowledge of the rock characteristics in the layered sequence, as well as of the general geologic setting in which the gravity survey is conducted. The method is of value to the sedimentologist in locating placer deposits such as buried river channels, filled basins, faults and dikes, and many geologic anomalies based upon density contrasts.

Variations in the magnetic susceptibility of rocks are almost entirely determined by the magnetite content. Although there are many magnetic minerals in sediments, none have such widespread occurrence as magnetite. If the geological and mineralogical associations in sedimentary rocks are well understood, it is possible to map the distribution and attitude of such formations. For this purpose, measurements of the earth's magnetic field in a bore hole, at the surface, or from aircraft may reveal valuable information. The magnetometer is the oldest prospecting device used by man which has continued to the present day. Like other geophysical instruments, it does not lead directly to the discovery of treasure, excepting for magnetic minerals; therefore, its usefulness is confined to the indications which it gives on structure, stratigraphy, and the distribution of magnetic materials.

In applied sedimentation the magnetometer may be used for the broad scope of mapping the distribution of magnetite-bearing rocks or for local surveys for ore bodies. Its use has been most widespread in prospecting for ore, relatively less for petroleum surveys than other methods. Because of its low cost and speed of operations it is well suited for broad reconnaissance surveys immediately after geologic mapping. Favorable areas isolated by the magnetometer are usually explored in further detail by other methods.

The electrical conductivity of rocks in a place is determined by two principal factors: (a) their water content, and (b) concentration of mobile ions. If the presence of conducting ions is systematically related to the occurrence of oil, gas, or minerals, electric resistivity surveys will be of value. These have been successfully conducted from the surface of the earth by employing a profile method which traverses lines of exploration related to the area under investigation. The presence of a conducting layer, such as a sand formation saturated with conducting water at moderate depths (not over 5,000 feet), may afford a convenient datum to which the resistivity measurements may be referred. By using the conventional four-electrode method, values of formation resistivity may be plotted along parallel lines of exploration to show the subsurface attitude of the conducting horizon. Modifications of this simple geologic setting reveal complicated pictures of fine detail. The presence of a layer of high conductivity near the surface will effectively mask more deeply buried features.

A modification of the electrical method is found in electric well surveys. Here direct measurements of formation resistivity and electric self-potential are taken from electrodes lowered into a well. A log of the variations in these two quantities is of great value in the development of petroleum production. It shows the presence of oil or gas, fresh or salt water, and striking variations in the properties of different types of formations, sandstones, limestones, and shales. The electric logging method has great promise in near-surface applications, as yet relatively undeveloped. The instrumentation is simple; its operation involves no great cost. Problems to which the method might be applied are the location of water supply, determination of bedrock beneath the surface and overburden, the location of faults, dikes, and other structural features related to construction engineering problems.

The measurement of the radioactivity of sedimentary beds in place offers striking correlation with electric measurements on the same formations. The reasons for these correlations reside in the particle size distribution of sediments and sedimentary rocks. In general, the fine-grained rocks, shales, and clays show the greatest radioactivity, whereas rocks comprised of coarser fragments, such as sandstones and conglomerates, show lower activity. Induced radioactivity employing neutron radiation is also of value in identifying sedimentary sequences. Both methods have undeveloped potentialities in the same series of problems outlined for electric applications.

The search for minerals and ore deposits by geophysical means in the United States has not greatly advanced the science in recent years. Within the mining industry there seems to exist an attitude which is difficult to explain. In the past the merits of any geophysical survey have been largely judged by the amount of ore the survey produced. Surveys failing to produce ore have been condemned without critical examination, and there has been no opportunity to profit from these failures. The mining industry has not operated under the philosophy which the petroleum industry has found so successful, that is, to develop geophysics on as broad a base as possible. The result is that full development of mining geophysics in the United States has not taken place, and we now find ourselves practically in the same position as in 1925.

In Canada more success has attended the applications of geophysics. Magnetic and electric methods are in general use. Much new ore has been found from these applications. The airborne magnetometer offers considerable promise in the development of large virgin territories which are otherwise inaccessible. The advances to be expected in this field in the immediate future are those in transportation and operational facilities. Probably no revolutionary discoveries in geophysical principles should be expected.

ENGINEERING GEOPHYSICS (INCLUDING SOIL MECHANICS)

In the preceding section it was intimated that some exploration techniques might be applied with advantage to problems in engineering. There are many problems, closely related to each other, which would benefit by a modest effort in research and development. These problems are recognized by many, but there seems to be no widespread understanding that geophysics might be of aid in their solution. Unlike the petroleum industry, there has been no sponsoring benefactor to pay for development costs. It is possible that state and federal agencies or other institutions may attack these problems to advantage. The general principles outlined here are intended to guide those wishing to pursue future courses of action. These principles will be illustrated by a few examples.

In the selection of a site for the foundation of a dam, bridge, aqueduct, viaduct, highway, or a large building construction, the construction engineer and the contractor seldom have adequate data on the subsurface underlying the site. Current practice is to subcontract for a series of boreholes to bedrock, or to such depths that piles can be driven, to support foundations. In cases where bedrock is found it may happen that the rock encountered is a first layer, under which other unconsolidated material may lie, hidden from sight. The location of the boreholes is usually such that the profile of bedrock surveys is assumed to be smooth between boreholes. It is rare that enough boreholes are drilled because their cost is very high.

Where piles are driven, the bearing capacity is calculated from empirical formulas based upon assumptions and experiences which may be quite removed from those of the site under consideration. Sample cuttings of boreholes in unconsolidated materials display properties quite unlike those encountered *in situ*.

Foundation sites for many large structures have often been selected without knowledge of subsurface geology, subsurface geological features such as faults, buried channels, and basins filled with unconsolidated materials. Many famous structures are in danger because of these oversights. Some of the errors could have been prevented by the employment of competent geologists when the selection was made, but they might have been unable to detect hidden features which could be brought to light by geophysical methods.

The properties of soils as components of structures and foundations require more convenient and precise methods of determination. Consultants in the field of soil mechanics are casting about for devices which they may use for testing soils and their properties. It is difficult to prescribe one formula to meet all these needs. This is especially true because prevailing concepts in soil mechanics generally omit the geological point of view, the concept of active processes which affect the soil constantly throughout its life.

The foregoing examples illustrate the need for research and development in the field of applied sedimentation. In all these problems it is clear that an application of the existing techniques of geophysics will bring early assistance to bear. Already there are competent resources of personnel and facilities if the way is made clear for their utilization. The difficulty is to find sponsoring agencies who will coordinate these efforts. This is a new borderline science which it seems important to develop. It is hoped that these remarks may be brought to the attention of those in position to chart future courses of action.

GEOPHYSICAL AIDS TO GEOLOGIC MAPPING

One of the functions of the U. S. Geological Survey and of state geological surveys is to map the geology and the mineral resources of our country. In this function the surveys have for many years carried out a comprehensive program of geologic and topographic mapping. The locations where these surveys have been completed are those where the needs were greatest. At first, immediate developments followed closely upon the completion of adequate maps. This function has been extended to subsurface mapping where underground workings have been opened by mining operations and by the drilling of wells for oil, gas, and water.

We have come to a phase in the development of our country's mineral resources where these methods of geologic mapping greatly restrict the nation's development. It is now time to think of ways of large-scale mapping of subsurface geology, without competing with the functions in this realm normally exerted by commercial operating companies. To expand the mapping function it is inevitable that resort be made to geophysical methods. The seismograph has demonstrated well its ability to portray the attitude and depth of key horizons in sedimentary provinces. If structure and stratigraphy are concealed beneath a cover of overburden, alluvium, or valley fill, there is no better method of unveiling subsurface conditions than by the use of geophysics. Its cost is insignificant compared with that of drilling an adequate number of holes in a virgin territory. The distribution of data yields a much better density than other methods permit. The prevailing lack of appreciation of geophysical methods may be attributed in part to lack of understanding of the method, but also to lack of facilities and trained personnel in the United States. Since it is the proper function of the geological surveys to develop new methods of exploration and survey, it is hoped that this area of investigation may be developed in the near future. Already we have valuable examples of the contribution made to the nation's resources by the airborne-magnetometer maps which the U. S. Geological Survey has produced in the Lake Superior region, in the magnetite, lead, and zinc deposits of New York, in the central portion of the state of Pennsylvania, and elsewhere. These reconnaissance maps will be of value for many years to those who follow with ground surveys of greater detail.

DEVELOPMENT OF ORE DEPOSITS

Since the mining industry has not developed geophysical methods for exploration to a high degree, it is conceivable that a beginning might be made in the development of existing ore deposits. There are many problems in the extension of working properties to which geophysics would make substantial contributions. These would employ the conventional instruments and techniques of the principal kinds discussed herein. Close correlation by the geophysicist and the mining geologist is likely to develop profitable areas of application through the extension of known ore deposits. None of the principal geophysical techniques has been exhausted in this connection. It seems likely that valuable advances could be made in this field at relatively small costs.

DEVELOPMENT OF PETROLEUM PRODUCTION

In sharp contrast to the mining industry, the petroleum industry has expanded large numbers of geophysical techniques to the benefit of producing properties everywhere. The industry is quick to take advantage of every scientific fact related to the occurrence and production of oil and gas, with the consequence that scientific aids to oil production have been developed to a high degree, a degree that is rare in all American industry. The wisdom of this policy is found in the excellent returns of producing divisions.

Properties measured in the course of petroleum production follow:

(*a*) Electrical conductivity of reservoir rocks and their contained fluids.
(*b*) Electrical self-potential.
(*c*) Spectrographic analysis of reservoir rocks and contained fluids.
(*d*) Radioactivity of rocks and fluids.
(*e*) Induced radioactivity of rocks and fluids.
(*f*) Fluorescence of reservoir fluids.
(*g*) Mineralogical composition.
(*h*) Insoluble residues of sedimentary rocks.
(*i*) Clay mineral content and identification of species.
(*j*) Acoustic impedance.
(*k*) Density.
(*l*) Magnetic susceptibility.
(*m*) Colorimetric determinations.
(*n*) Porosity.
(*o*) Permeability.
(*p*) Fluid saturation.
(*q*) Composition of connate fluids, including pH.
(*r*) Temperature distribution.
(*s*) Seismic wave velocity.

These measurements of conditions of sedimentation suggest the large number of possibilities which have not been developed in geophysical applications to problems outside the petroleum industry.

MILITARY AND NAVAL PROBLEMS

The application of geophysics to these problems involves many subjects which are classified for military security. Some of the published articles on the subject show possibilities of use in other areas which approach those of the petroleum applications in number. It is promising to observe that under the stimulus of military necessity many established geophysical techniques have developed new values in a different setting. Some of the spectacular performances of World War II involved highly coordinated programs in the geophysical sciences. If it had not been for combat teams in oceanography, meteorology, and military geology, many of our task forces would have suffered severely at the hands of the enemy.

SUGGESTED PROGRAM OF ATTACK

For the sedimentologist who wishes to employ geophysics as an aid to a solution of his problems, it is recommended that the principles discussed above be applied through the study-group method. Unless one is contemplating a long period of geophysical activity it is inadvisable to recommend that full knowledge of the contributing fields be acquired. This would be a difficult task in itself, not to speak of the time involved. In many organizations where special points of view are indicated, good progress is made in relatively short time by organizing a small group of specialists with a leader whose knowledge and experience are broad enough to give him a general understanding of the language of each member of the group. In this way no possible interrelations will be lost, and the productivity of such a group, under able leadership, will be surprising. It should be the policy of the study-group leader to encourage all worth-while suggestions during a stage in the program where criticism and evaluation are not present. Until the group is accustomed to working together, there may be some whose natural timidity will prevent them from delivering all their ideas for the benefit of the meeting. It has been found practicable to cover the entire field of research in a preliminary stage as suggested.

After the material so presented is organized, it will be desirable to evaluate individual ideas. For this purpose it is helpful to have one member of the group who is outspoken and straightforward, and who commands the respect of others for his clear thinking and power of analysis. The function of the group at this stage is to screen out all valuable material and to discard that which is unsound or irrelevant. The third stage arrives when the sound material has been organized and resubmitted to the group. At this point important decisions will be made, strong convictions will be formed, and there will arise a surprising unanimity among the members of the group as to the logical procedures for the future. It may develop during the course of the meetings that new data or new interpretations are required. For these functions the chairman may appoint small working groups or individuals who will assemble and present the new materials in such manner that all members of the group may make use of them. The timing of the group meetings will depend upon the amount of this detailed work required.

One brief caution may be noted. In some group meetings normal scientific procedure and good judgment have been overridden by an emotional factor. Some member of the group should be given the responsibility of watching for this element. In one case a group of eminent scientists was completely won over by a "spellbinder" presentation which lay undiscovered for many weeks. Only under long and careful examination did the weakness of the group's conclusions become evident. It is unlikely that any member of that group will ever become a victim of similar circumstances again.

PROBLEMS SUGGESTED FOR FUTURE RESEARCH AND DEVELOPMENT

ENGINEERING GEOPHYSICS

The examples outlined above in this field are largely confined to problems of the ground, ranging in depth from the surface of the earth to a few hundred feet. In terms of the accuracy and resolving power of geophysical methods applied to exploration, many of these near-surface problems offer great promise of valuable solutions. Sedimentologists confronted with these problems should be readily able to develop methods of attack when equipped with a good working knowledge of applied geophysics. The barrier to rapid progress in this field of development seems to lie in the transfer of knowledge and understanding from existing areas of application to those requiring geophysical aids for the first time. It is obviously impossible to impart in a short time the full scope and limitations of geophysical methods to problems of applied sedimentation. The outlook is not hopeless, however, and it is believed that, equipped with a general outline, the student of applied sedimentation may select from the literature the educational material he needs for his tasks. From a brief reading of the material of interest in the list of references at the end of this chapter, the geologist interested in sedimentation should quickly place himself in position to discuss the problems in further detail with expert geophysicists. By these means it is believed that an adequate dissemination of geophysical knowledge may be accomplished.

Seismograph. The principal function of this instrument is to measure depths to key horizons of sediments and rocks. A derived function is to identify such horizons, enabling one to establish correlations of stratigraphic or lithologic equivalents over their lateral extent. It may also show the presence of discontinuities and transitions in sediments and rocks. From seismic data it is possible to infer the distribution of sedimentary and rock formations, their dimension, shape, attitude, and identity. Often it is possible to infer something of the detailed nature of a formation such as, for example, the distinction between rocks which are massive and those which are composed of a series of stratified layers.

The gravitymeter. This instrument may be adapted to near-surface problems in the detection of deposits of sediments, rocks, and minerals which exhibit density contrasts. The resolving power of the method depends primarily upon the numerical magnitude of the gravity contrasts and the size and distance of the anomalous formation from the surface. It gives its best results on flat terrains; uneven topography introduces errors which cannot always be accounted for. If the gravity contrasts are associated with structural features, these may often be correctly inferred by the intelligent interpretation of the data and their correlation with geologic data on the prospect. The successful application of the gravitymeter extends to density contrasts in excess of 0.1.

Ground magnetometer surveys. These surveys show a high degree of resolving power for buried deposits of magnetic rocks and minerals, if the effective magnetite content of such minerals is at least 0.1 percent. Masses of such formations can be detected and outlined satisfactorily. Negative anomalies may also prove significant, because they show the presence of formations of low susceptibility in a region of normally higher values. Estimates of depth based upon magnetic data are, like those of gravity data, not entirely satisfactory unless the limits of depth estimates are supported by good geologic data.

Electrical and electromagnetic methods. Such methods are of immediate value in the determination of depth of overburden, thickness of soil, and depth to ground water, and in the differentiation of types of rock and sediments. The accuracy of depth and thickness measurements is good, depending upon the amount of detail applied in the field. In locating water supply, buried gravel deposits, placers, and geologic discontinuities involving changes in conductivity, these methods are cheap, rapid, and effective. The tools are readily available, awaiting only their application to problems in applied sedimentation.

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Byerly, Perry (1942). *Seismology:* Prentice-Hall, New York, 256 pages. An advanced text on "pure" seismology, containing data and discussions on earthquakes, their nature, cause, effects, distribution and frequency.

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Leet, L. Don (1938). *Practical seismology and seismic prospecting:* D. Appleton-Century Co., New York, 430 pages.

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Meinzer, O. E. (1923a). The occurrence of ground water in the United States, with a discussion of principles: *U. S. Geol. Survey,* Water Supply Paper 489, 321 pages. Dr. Meinzer's famous statement of fundamental principles. Now out of print, but available at libraries.

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Muskat, M. (1937). *The flow of homogeneous fluids through porous media:* McGraw-Hill Book Co., New York, 763 pages. An exhaustive treatise, theoretical and mathematical, of the technical problems encountered in oil-field production.

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No. 77 (1931). *Volcanology.* 77 pages.

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No. 79 (1931). *Meteorology.* 289 pages.

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Sverdrup, H. U. (1942). *Oceanography for meteorologists:* Prentice-Hall, New York, 250 pages.

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American Institute of Mining and Metallurgical Engineers, *Transactions,* New York, published irregularly as separate volumes:

Geophysics and geophysical prospecting, vol. 81 (1929), 676 pages; vol. 97 (1932), 510 pages; vol. 110 (1934), 583 pages; vol. 138 (1940), 489 pages; vol. 164 (1945), 426 pages; also vol. 74, pp. 3–28, contains one paper on electrical prospecting. Professional articles on all phases of geophysical exploration under a series of Technical Papers sponsored by the A.I.M.E. Committee on Geophysics. Covers case histories, theoretical, mining, laboratory and field tests, with a series of papers on geophysics education.

Petroleum development and technology, published annually as *Transactions.* Contains professional articles on the theory, research, and engineering of petroleum production and reservoir studies. For late years see *Transactions,* vol. 160 (1945), 665 pages; vol. 165 (1946), 292 pages; vol. 170 (1947), 279 pages. Beginning in 1948 a new series called *Statistics of oil and gas development and production* was started; 514 pages in the 1948 volume.

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Carnegie Institution of Washington, Washington, D. C. List of publications available on request. A comprehensive subject list of scientific geophysics, containing reports by staff members and others sponsored by the Carnegie Institution under the direction of the Geophysical Laboratory and the Department of Terrestrial Magnetism. Invaluable for fundamental researches on the Earth.

Journal of Geophysical Research (formerly *Terrestrial Magnetism and Atmospheric Electricity*), published by the William Byrd Press, Sherwood Avenue at Durham Street, Richmond 22, Virginia. Contains papers on all subjects in scientific geophysics (as distinguished from practical or industrial geophysics).

Royal Astronomical Society, *Monthly Notices,* Geophysical Supplement, London, England. Contains brief articles and notes on scientific geophysics.

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U. S. Coast and Geodetic Survey, *Seismological Publications,* Department of Commerce, Washington, D. C. List of publications available on request. Covers many scientific phases of seismology and other geophysical subjects. Valuable detailed information on design, installation, and operation of observatory equipment; the collection, reporting, reduction, and interpretation of data.

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Chapter 5

PRINCIPLES OF SOIL MECHANICS AS VIEWED BY A GEOLOGIST *

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Soil mechanics, or the study of the mechanical properties of unconsolidated earth materials, is one of the youngest and most promising of the border sciences that lie between the quantitative realm of engineering and the qualitative domain of geology. *Soil,* as used in soil mechanics, is not simply the organic-rich surface layer of the agriculturist and the geologist. The scope of the word has been broadened to include all granular earth materials which cannot be called hard rock. Unconsolidated sediment, regolith, and mantle rock, irrespective of proximity to the surface, are classed as soil.

Although a few short decades ago soil mechanics was only an academic specialization in the sprawling technology of civil engineering, it has rapidly grown to become one of the indispensable tools of modern engineering. Within this time the more scientific methods of soil mechanics have almost completely replaced the empirical methods that had traditionally been employed for the design of foundations, retaining walls, earth slopes, earth dams and dikes, and highway subgrades. As part of this new engineering activity, site investigations and soil-sampling techniques have been developed to a point of high refinement, and soil-testing laboratories have sprung into being in many parts of the world.

Soil mechanics already has had some impact on geology. Most engineering geologists today are obliged to deal quantitatively with the mechanical properties of unconsolidated sediments, and, as a result, geologists are developing an active interest in soil mechanics. This is particularly so because the close collaboration between geology and engineering, which characterizes much of today's engineering planning, demands that both groups speak the same language and recog-

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nize the same problems in the same terms. However, a fact less well recognized by geologists is that soil mechanics can be of great value to other fields of geological investigation. Tools have already been fashioned by engineers which geologists could profitably use in such problems as estimating the former depth of burial of clays, the critical conditions of instability in landslides, and the active pressures necessary to produce shearing and failure in soils. But perhaps the greatest value soil mechanics can have for geology is the introduction of mechanical concepts into geological thinking. The mechanical techniques are already well-advanced in soil mechanics. The geologist may be able to extend these methods to hard-rock problems and thereby in time derive a more refined understanding of the nature and intensities of earth stresses.

On the other side of the ledger, there is no doubt that soil mechanics at this stage of its development needs the geologist's sensitive understanding of the variations of earth materials. Furthermore, there is a growing recognition that additional progress in soil mechanics awaits the solution of a number of problems concerning the fundamental properties of soils which fall into a common ground between geology and soil science. In view of these common needs it does not seem unrealistic to expect a close harmony between geology and soil mechanics in the near future. It is therefore the purpose of this chapter to arouse the geologist's curiosity in soil mechanics. For a formal introduction and ensuing acquaintanceship with the subject the student is referred to the list, at the end of this chapter, of several excellent textbooks on soil mechanics which have appeared in recent years.

WHAT IS SOIL MECHANICS?

The quantitative appraisal of the stress-strain relationships of soils in the engineering works of man is the subject of soil mechanics; or, to quote Professor Terzaghi (1943, p. 1), "Soil mechanics is the application of the laws of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles produced by the mechanical and chemical disintegration of rocks, regardless of whether or not they contain an admixture of organic constituents."

The investigation of the mechanics of soil behavior is the logical extension of the engineer's interest in the strength of materials. The strength and elastic constants of steel and concrete, for example, have long since been determined with satisfactory precision. This knowledge has permitted engineers to design highly economical and safe structures using these materials. Because soils form an integral part of most structures, whether as foundation or as construction material, it follows that modern structural design should include a rational analysis of soils. However, of all the important construction materials used by man, soil is the only one which, because of its complexity and variability, cannot be reduced to relatively simple and universal numerical values. This is apparent when the complexity of factors affecting soil behavior is recognized. The mechanics of soil certainly must include such considerations as compressibility, rigidity, permeability, and the elastic and plastic properties. Furthermore, the anisotropic nature of most soils and the difficulty of deriving a statistical expression for the deviations from homogeneity complicate still further any attempt to reduce soil behavior to simple terms.

It was, however, the initial problem of soil mechanics to decide, first, if any sort of reduction was possible and, then, how such a reduction, simple or otherwise, could be made. The problem initially resolved itself into the following questions: (1) What soil properties affect mechanical behavior? (2) How can these properties be measured? (3) What are the stress distributions within a soil mass? (4) How do soils act when subject to stress? What was needed, in short, was a knowledge of the stress-strain relationships in any soil mass.

All soils consist of a three-phase system: solid, water, and gas. A thorough understanding of soils must therefore involve an understanding of the interaction of all phases. Although there are notable exceptions, it can be said that soil mechanics is mainly concerned with the interaction features, or the aggregate properties, of soils. Research into the properties of the individual phases, and in particular into the properties of the solid or granular phase, is carried on mostly in mineralogy, sedimentation, soil physics, and soil chemistry.

PRINCIPLES OF SOIL MECHANICS

General

The many soil conditions, with their attendant engineering problems, that are analyzed by soil mechanics can be grouped into three categories: (1) those in which overstressing produces rupture or failure of the soil, (2) those in which the moderate stress conditions produce only deformation of the soil, and (3) those in which permeability of the soils is the important factor (Table 1). These problems can be further classified into those in which the hydraulic properties (the condition of the pore water) of the soil play the principal role, and those in which the strength of the entire soil mass is involved, that is,

TABLE 1

THE PRINCIPAL PROBLEMS OF SOIL MECHANICS

	Soil Properties	
	Strength properties	Hydraulic properties
Stability problems	SLOPE STABILITY, evaluation of critical height of slopes in cuts, fills, etc.	SEEPAGE FORCES, effect of pore-water pressures on stability of dams, dikes, slopes, walls, etc.
	EARTH PRESSURES, prediction of the magnitude and distribution of soil pressures on walls, timbering, and other retaining structures	
	BEARING CAPACITY, evaluation of safe bearing capacity of footings and piles	
Deformation problems	SETTLEMENT, elastic and plastic deformation of soil under footings, piles, and other concentrated loads	CONSOLIDATION, compression of soil by external load or capillary pressure due to extrusion of pore water
Permeability problems		PERMEABILITY, computation of rate of flow of water through dams, dikes, and natural embankments, or through subsoil of water-retaining structures.

where both the solid and the liquid phases of the system are of decided importance.

In soil mechanics theory all soils are considered to be granular aggregates consisting of discrete solid particles and interspaced voids. The solid particles are mutually supporting, each grain pressed against, and kept in place by, neighboring grains. The voids, or pore spaces, of soils are generally filled with water and air, and more rarely with minor amounts of other gases. Beneath the water table the voids are entirely filled with water except for dissolved and entrapped gases.

The granular nature of soil structure is found in clays as well as in the more obviously granular silts, sands, and gravels. However, the simple granular concept becomes somewhat complicated in clays, for it is known that in these colloidal soils the boundary between the solid grains and the fluid-filled voids is not always sharply defined. The presence of relatively thick layers of adsorbed water molecules on the surfaces of clay colloids introduces forces in the soil system which cannot be readily explained in terms of an ideal granular soil.

Most soils possess appreciable shearing strength. In the more coarsely grained and non-cohesive soils, the source of this strength is the friction developed at the points of contact of the soil grains. The greater the pressure between soil grains, the greater is the force necessary to displace one grain in relation to another.

The importance of intergranular friction on soil strength can be demonstrated by a simple laboratory experiment. A soft rubber bladder is filled with loose, dry sand. As can be readily visualized, the sand inside the bladder is easily displaced by small stresses, such as the prodding of a finger. However, when a suction pump is applied to the bladder and the air from inside the bladder is excluded, the mass of sand is seen to develop a rather surprising rigidity. It will be found to resist not only the prodding of a finger but also the weight of a heavy book placed on top of it. This sudden development of strength is the result of increased intergranular pressure in the sand which is brought about by the sand grains being made to bear the weight of the atmosphere pressing against the outside of the bladder. The intergranular pressures developed in this little experiment are roughly of the same magnitude as those in dry sand buried at a depth of about 20 feet, for at that depth the weight of overburden is about equal to the atmospheric-pressure load in the experiment.

This experiment demonstrates another important property of soil, namely, that the stresses in the pore fluids have a direct effect on the strength of the soil. Indeed, the strength of a soil is affected by all stresses within the soil system. This interdependence can be simply demonstrated in the laboratory in another way. The apparatus consists of a tank containing loose sand. Water is poured into the tank to a level above the top of the sand. When we attempt to dig a hole in the submerged sand, we discover that it is impossible to maintain a steep face in the excavation. Sand flows in from all sides, and the slopes immediately assume a low angle of repose. On the other hand, when water is allowed to flow down through the sand and out an opening in the bottom of the tank, we discover that we are able to dig a steep face in the submerged sand, and, in fact, with care we can make a vertical face. Finally, if the direction of flow in the experiment is reversed and water is forced up through the sand, allowing the overflow to drain out the top of the tank, the sand suddenly becomes a "quicksand." This is shown by the fact that a small weight, which had previously rested on the submerged surface of the sand, now sinks down into the sand.

The explanation of these three related states of strength lies in the effect of the pore fluids on the intergranular pressure. The friction of downward-moving water on the sand grains acted as an additional downward stress and thus increased intergranular pressures. The resulting increase in strength was expressed by the steep slopes that were maintained in the sand. On the other hand, the upward-moving pore water produced the same frictional effect, but in the opposite direction. The upward stresses it induced cancelled the effect of the gravitational stresses. If the water moved upward with a great enough velocity, the sand grains would go into suspension as sediment and be carried out of the top of the tank.

In addition to intergranular friction, cohesion is another property which contributes directly to the shearing strength of soils. As is well known, it is futile to attempt to mold a sand castle in dry beach sand; whereas the same sand, when moistened, can be fashioned into near-vertical walls and turrets. Clay, on the other hand, can be molded into vertical walls, and even into intricate overhangs. Moreover, dry clay maintains its shape and, unlike sand, develops a high strength. This ability of soil granules to hold together when unsupported is called cohesion.

Cohesion can result from a number of conditions in a soil. For example, the cohesion of the moist beach sand is the result of capillary tensions, whereas that of the clay is ascribed to the cohesive bonds between adsorbed layers of oriented water molecules on the surfaces of the clay particles. Cementation of different kinds may also be considered a form of cohesion.

It is apparent, therefore, that the shearing strength of soils is the sum of the two factors, cohesion and intergranular friction. This was expressed by Coulomb (1776) in an equation that has become classical in mechanical theory:

$$s = c + n \tan \phi$$

where s is shearing strength along any plane, c is cohesion, n is the pressure normal to the plane, and $\tan \phi$, or the tangent of the angle of internal friction, is an expression of the frictional properties of the material. However, today it is known that the validity of this equation is somewhat limited. The relationship between s and n for cohesive soils is more complicated than the equation indicates.

Sampling and Testing

The several fundamental mechanical properties of soils that have just been described serve as a point of departure for much of soil mechanics theory. In practice there are many ways of applying soil mechanics to quantitative soil problems. Each set of geological conditions, as well as each type of construction, demands separate consideration and a different treatment. In general, however, soil investigations follow a pattern of sampling → testing → analysis. The prediction of soil behavior that is the result of this procedure is therefore dependent on (1) the representativeness of the samples, (2) the pertinence of the testing, and (3) the pertinence of the mechanical theory used in the analysis.

Soil samples are of two types: (1) undisturbed samples, in which the soil is removed as an integral lump, thus preserving its intergranular relationships; and (2) disturbed samples, in which no attempt is made to preserve the structure of the soil. Much thought has gone into the design of undisturbed samplers for use in boreholes. A large variety of types have been built, most of them based on a removable sampling tube with a minimum of side friction and with some type of valve arrangement to prevent loss of the sample on withdrawal.

Soil testing is of two basic types: field testing and sample testing. Field testing is the measuring of a soil property directly in the field without isolating a sample. The driving of penetration cones, test piles, and other resistance devices into the soil to determine strength or bearing capacity is an example of field tests. Results from such tests are generally empirically applied. Field testing is much more common in the countries of northern Europe, where widespread uniform soft Quaternary deposits prevail, than in the United States.

Sample testing can be divided into three categories: (1) classification tests for index properties; (2) empirical properties tests—direct application; (3) basic properties tests—indirect application. The second and third types are simulative tests.

The common classification tests employed in the United States include such procedures as mechanical analysis for grain-size distribution and liquid and plastic limit, to mention only a few. The principal value of classification tests is for correlation and record. The accumulation of index data, such as plastic index or grain-size distribution, when tied in with observations of soil performance, contribute to the building up of an empirical understanding of soil properties. In fact, much soil mechanics specification for foundation design is done without the aid of the more complicated soil tests and is based

TABLE 2

SOME OF THE MORE COMMON SOIL MECHANICS TESTS [1]

Index Properties Tests [1]	Simulative Tests	
	Empirical properties tests	Basic properties tests
Mechanical analysis Sieve Hydrometer Elutriation Specific gravity of solid particles Natural water content Degree of saturation (cohesionless soils) Liquid limit } Atterberg limits Plastic limit } Unconfined compressive strength	Standard "Proctor" compaction (moisture-density relations) California bearing ratio Various bearing tests	Consolidation Direct shear Triaxial shear Permeability

[1] See textbooks in bibliography for description of tests.

primarily on the experience and the sensitivity of the soils engineer to differences in soil types. The recognition of similar soils as expressed in classification tests is often sufficient to recommend similar soil treatment for different projects.

More interesting from the standpoint of soil mechanics techniques are the properties tests. These are tests to determine isolated soil properties which have a direct bearing on soil behavior. It is noted that they are simulative, which means that they attempt to reproduce, on a reduced and measurable laboratory scale, phenomena which occur or will occur in the prototype soil mass. The triaxial shear test is a good example. Here a cylindrical sample of soil is stressed axially under controlled lateral confinement. This is a close approximation of an unbalanced stress system operating on a buried cylindrical element of soil. This type of soil test yields strength moduli (cohesion and angle of internal friction) which are then applied to the analysis of the full-scale stability problem. The triaxial shear test is, therefore, a basic properties test.

The empirical properties tests are also simulative. The usefulness of these tests lies in the empirical correlation between field performance and test data. Inquiry as to "why" does not form a necessary part of its application. As an example, the standard "Proctor" compaction test may be cited. This test is used to determine the compaction properties of soil when placed as fill. The basis for this test lies in the well-known fact that a given soil, depending on its moisture content, will compact to different densities with the same amount of rolling. The Proctor test is, therefore, a standardized test which determines the optimum moisture content for maximum density by pounding into a cylindrical mold with a standard weight, dropped from a standard height, representative soil samples with different moisture contents. This operation simulates the energy transmitted by the tamping of a sheep's-foot roller on the soil in the field. The data from the Proctor compaction test are applied directly in construction, without further analysis, merely by specifying that all fill be compacted with the determined optimum moisture content.

Atterberg Limits

With increasing water content a clay changes consistency and passes from a solid state through a plastic state to, finally, a liquid state. Each soil possesses a rather characteristic set of limits to these three states. These limits of consistency are arbitrarily fixed by a standardized testing procedure which was first proposed by Atterberg and which has come to be called the Atterberg limits (Terzaghi and Peck, 1948, pp. 32–36). The water content defining the upper limit of the plastic range is called the *liquid limit,* and that defining the lower limit is the *plastic limit.* The numerical difference between these two limits for any soil is the *plasticity index* of that soil.

Statistical studies of the Atterberg limits of many clays (Casagrande, 1947) have shown some interesting relationships among a number of soil properties. It has been noted, for example, that the larger the plasticity index of a soil, the greater is its plasticity, its compressibility, and its dry strength. In addition, it has been found that, when the plasticity indices and liquid limits for a large number of clay samples coming from the same bed or from geologically related deposits are plotted on a graph, the data define a straight line (Fig. 1). Furthermore, the linear plots of clays of different geologic origin occupy different areas on the graph. It is also noteworthy that all the lines in Fig. 1 are roughly parallel.

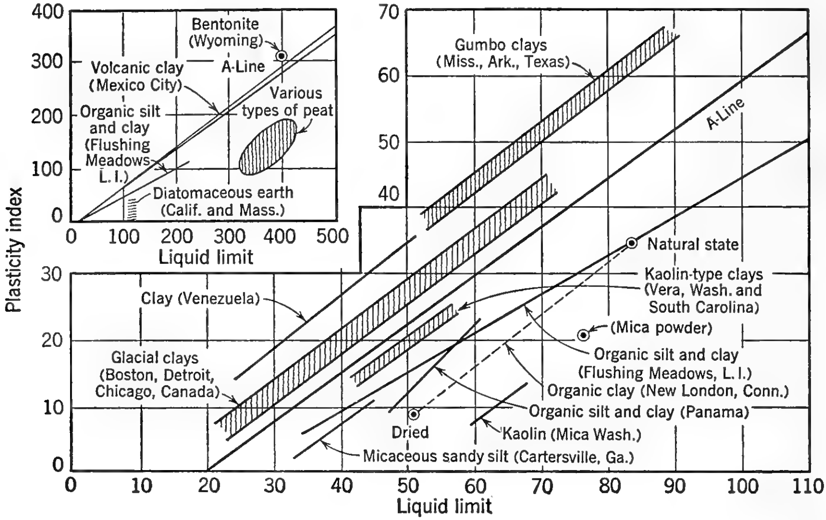

FIG. 1. Relation of liquid limit to plasticity index. (After Casagrande, 1947, p. 803.)

SLOPE-STABILITY ANALYSIS

When a deep road cut is designed, how does the engineer know that the slope will be stable? Or, for that matter, how can the geologist determine the quantitative conditions for landslides and the formation of land forms developed from mass displacements of soil? To answer this type of question a number of methods for the analysis of slope stability have been devised in soil mechanics. The following exposition is only a brief account of the basic principles; the standard textbooks should be referred to for more detailed explanation.

To determine the stability of a soil slope against sliding, the distribution of soil types behind the slope and in the toe of the slope must be known, as well as the position of the water table. Undisturbed samples of each soil type are obtained, and laboratory tests are made to determine their unit weights (weight per unit volume), cohesion, and angle of internal friction.

In general, it can be said that a slope will slide if there exists some surface within the embankment along which the resultant of all shearing stresses exceeds the total shearing resistance along that surface. To determine whether this is a possible condition for a given slope, a graphical method is widely employed. On a geological cross section (Fig. 2) taken at right angles to the slope, a possible sliding surface in the form of a circular arc is drawn more or less at random. In Fig. 2 this circle has its center at *O*. The circular-arc sliding surface is considered valid because detailed landslide studies have confirmed that most surfaces of sliding are strongly concave upward, although their exact form may be conditioned by such geological factors as bedding, fissures and fractures, the shape and distribution of different types of rock and soil, and the local concentration of pore-water pressures.

The force tending to produce sliding in Fig. 2 is the weight W of the

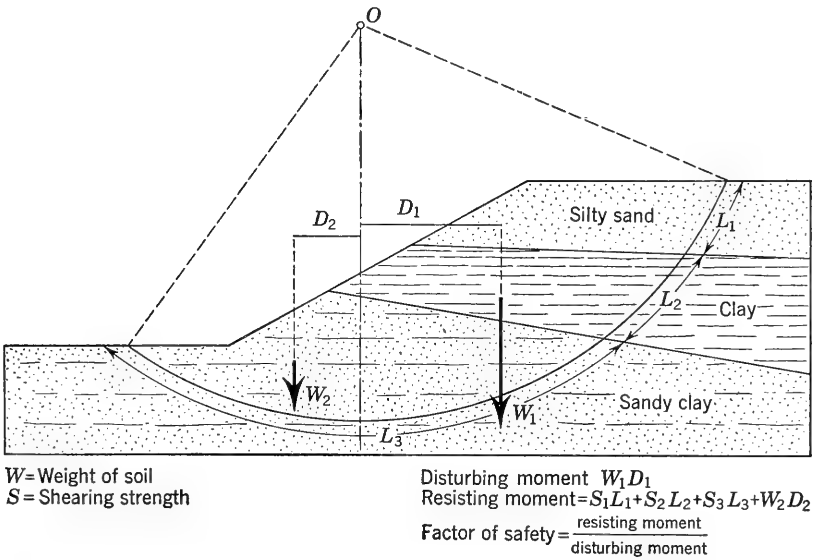

FIG. 2. Slope-stability analysis. See text for description; also Taylor (1948, pp. 406–479).

wedge of soils lying above the arcuate sliding surface and to the right of the vertical through the center O. It is measured as a moment about the center O of the circle. The force tending to resist sliding, or the resisting moment, is the total shearing resistance which can be mobilized along the entire length of the sliding surface plus the weight W' of the soils lying to the left of the vertical through the center O and above the sliding surface. It is also expressed as a moment about the center O. The lever arms for both moments are the horizontal distances between the centers of gravity of the two soil masses and the vertical through the center O.

In this analysis the total shearing resistance is computed by using Coulomb's equation, in which the values for cohesion and angle of internal friction are known from the testing results, and the normal pressures on the sliding surface are scaled or computed from the drawing

ing. The ratio of the resisting moment to the disturbing moment is the factor of safety of the circle. To complete the analysis, other circles are drawn and their factors of safety are computed. The circle having the smallest factor of safety is called the critical circle and is the surface most likely to fail. The factor of safety of the entire slope is that of the critical circle, and for a stable slope the factor of safety must exceed 1.

A number of factors limit the accuracy of the stability analysis. In the first place, the cohesion and angle of internal friction of many clays are far from constant, and the determination of their values is subject to much uncertainty. In fact, studies of many slides in homogeneous clays have indicated that the stability analysis can be appreciably simplified by assuming that the shearing resistance along the sliding surface is equal to half the unconfined compression strength of the clays. Secondly, in some circumstances the exact value of the stresses that are effective in any plane though the soil mass cannot be readily appraised, particularly when the soil is subject to seepage forces. In fact, when any part of the sliding mass lies beneath the water table, seepage forces have to be taken into consideration in the stability analysis. This calls for the construction of a flow net, an operation often characterized by considerable uncertainty. Thirdly, it is difficult to evaluate the many geological factors, such as the structural heterogeneities (cracks, fractures, cemented layers, small pervious beds, etc.) present in many soils. However, despite these limitations, shearing strength analyses play an important role in soil mechanics and have been used with considerable effectiveness.

CONSOLIDATION

The slow compression of saturated clays under load is a deformation problem based on the hydraulic properties rather than on the strength properties of the soil system. There has been deep interest in the solution of this type of problem in soil mechanics, and of direct interest to the geologist is that out of it has been developed a technique of value to historical geology.

It will be recalled that soils are a skeleton of solid particles with fluids filling the interspersed voids. If a volume of soils with voids entirely filled with water is confined laterally and subjected to vertical pressure, any reduction of volume (strain) occurs only if either of the following conditions is fulfilled: (1) if there is a reduction in volume of the solids making up the soil skeleton, or (2) if there is a reduction in volume of the voids. As it is assumed that the soil grains and the water within the voids are incompressible, a reduction in volume of the soil mass can come about only by the extrusion of some of the pore water. This process of the reduction in the volume of soils due to the extrusion of pore water is called *consolidation* in soil mechanics, a usage not to be confused with that of geology.

Because the rate at which water flows through clays is generally very low, there is a considerable time lag between the moment of application of a stress to the clay and the completion of the strain. This time lag is a function of the permeability of the soil.

In the laboratory, saturated samples of clays are tested for consolidation in a device called the consolidometer. In this device a small disk of soil, confined on the sides and bounded top and bottom by porous stones allowing free drainage of the sample, is subjected to loading. The consolidation, or change in volume, is measured by the displacement of the top surface of the sample. The loading is done in increments, and each succeeding load is applied only after consolidation has ceased for the previous load. The data from this test are generally plotted on semi-logarithmic paper, with the total consolidation for each load expressed by void ratio e (the ratio of total volume of voids to total volume of solids in the sample) as the ordinate and the load per unit of area or pressure p as abscissa.

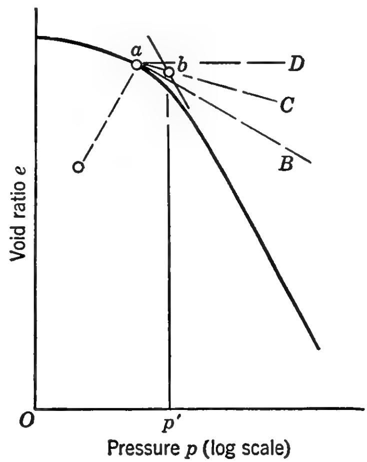

FIG. 3. Method of determining preconsolidation pressure. (After Casagrande, 1936.)

For the geologist, the interesting point is that it has been established that the shape of this e–log p curve (Fig. 3) reflects to a certain extent the history of loading to which a clay had been subjected during the geologic past. Clays, which at one time had been covered by the weight of a thick overburden or of an ice sheet, or in which there have been fluctuations in the water table, undoubtedly retain residual effects of this former early consolidation. Figure 3 represents a typical e–log p curve of a clay with a previous history of consolidation. The break in the slope of the e–log p curve is considered to be the expression of this earlier preconsolidation, and the pressure value corresponding to this break in the curve is roughly that of the former load. To establish the preconsolidation pressure more precisely, Casagrande (1936) has suggested a construction in which point b (Fig. 3) indicates the preconsolidation pressure p. This point is found in the following manner. At point a, which is the point on the e–log p curve with the smallest radius of curvature, a tangent aB and a horizontal line aD are constructed. Point b lies on the bisector aC of the angle between these two lines and is the intersection of the bisector with the upward extension of the steeply dipping straight part of the e–log p curve.

In an interesting paper on some postglacial clays, Skempton (1948) has recently demonstrated that this method for estimating preconsolidation loads is essentially correct. Other workers, however, have experienced difficulties in reconciling the computed preconsolidation loads with what was known of the histories of the clays. Greater interest of geologists in this work may reveal that present imperfections are due to limitation in our knowledge of the properties of clay and in our knowledge of the complexities of the geologic past.

RATIONAL BASIS OF SOIL MECHANICS

The rational method of soil mechanics is a process that should be familiar to the geologist. The long road that starts with facts, leads through operations, and terminates with inductive inferences—the road that is typical of much of geological thought—also characterizes soil mechanics.

At the beginning of every new job the engineer is confronted simply with a certain volume of soil, its properties unknown, its exact dimensions depending more upon the nature of the construction and to a lesser extent upon the nature of the soils; for instance, heavy structures stress soils to greater depths than light structures, etc. The engineer's problem is, therefore, to determine the pertinent physical properties of the unknown, which is the soil mass. This is done, as we have seen, by (1) observation, (2) sampling, (3) testing, and (4) analyzing. As a result of the sampling, testing, and analytical procedure, the engineer hopes that he has found out all he has to know about the stress-strain relationships of the soil mass in order to insure the safety of his structure. However, he arrives at this position by virtue of a number of assumptions, which, it must be acknowledged, may affect the accuracy of his prediction. It is assumed, for example, that all significant soil types in the mass are known and that the samples tested are typical of each type and are in the same condition as the soil in place. Furthermore, it has to be assumed that the mechanical theories applied are pertinent to the problem and that the rigors of the mathematics are applicable to the statistical qualities of the soil mass. These qualifications do not, however, affect the validity of the analytical process. All applied sciences involve a similar chain of facts and inferences. If soil mechanics not infrequently falls short of the accuracy that numerical answers imply, so does geology in its more quantitative aspects. Ore is not always found where predicted by the mining geologist on the basis of his geometrical projection of strike, dip, and fault displacement. Geologists recognize that in such cases the error does not lie with the geometry or with the process of analysis, but rather with the fact that, for lack of a thorough understanding of what happens to rock under all conditions, the geologist is forced to rely on simplified and idealized assumptions.

THE ROLE OF GEOLOGY IN SOIL MECHANICS

There is little need to emphasize the close relationship between geology and soil mechanics. Soils form the raw material of both sciences. Soil mechanics has, however, limited its interest principally to the behavior of soil, whereas geology has confined its interest to the origin and, to a lesser extent, to the substance of soil. The division between these interests is not always clear-cut; and the origin, substance, and behavior of soils are probably as intimately interrelated as are the human body and the human mind, two man-devised subdivisions which tradition has somewhat arbitrarily relegated to the physician and the psychiatrist.

A study of the most recent soil mechanics literature reveals that soil mechanics is looking more and more to geology to explain certain phases of soil behavior which heretofore had been taken somewhat for granted. Unfortunately, the soils engineer is rarely a geologist. Indeed, he generally has all he can do to pursue the complexities of his own specialty without embarking on those of geology. Geologists are, therefore, needed to cooperate with soils engineers if modern soil studies are to be carried out effectively. There are three ways in which the geologist can help the soils engineer to arrive at a better estimate of behavior:

(1) The geologist can determine the type and degree of anisotropy (variability) in soils. This is especially important in stability and hydraulic studies. Minute details of fissuring, stratification, and changes in texture, which may not be noticed by an untrained observer, are commonly of great importance to the strength of a soil mass. Such details can be detected more readily by the geologist, partly because of his habitual concern for such detail and partly because of his ability to deduce such detail from considerations of the origin of the deposit. The slow deepening and widening of shrinkage fissures in some clays

has caused many serious slides in deep cuts that had been perfectly stable for years. Testing of samples of these clays for shearing strength gives absolutely no indication of the specific weakness from which the soil eventually failed.

Many, if not most, landslides and soil failures are due to the development of high pore-water pressures. The evaluation of the hydraulic properties of soil is based primarily on geological conditions which often are so insignificant as to escape detection by all but the trained geological observer. Small pervious or impervious layers may influence the path of pore-water movement and the localization of pore-water pressures. The eventual failure may occur in a way entirely neglected in the stability analysis. In such cases, the strength of the predominant soil has no bearing on the strength of the slope, and it is the geological interpretation of structural relations that gives the clue to specific weaknesses.

(2) The geologist can reconstruct the history of a clay deposit and in this way roughly compute the type, duration, and amount of the preconsolidation load. Knowledge of this kind is of value in interpreting consolidation, settlement, and shearing-strength data in many clays.

Surficial clays may possess very much higher strength than deeper clays, owing to changes of the ground-water table. With each lowering of the ground-water table, surface clays experience a renewal of consolidation due in part to desiccation and in part to the increase in load resulting from the reduction of buoyancy. This process may not necessarily affect the deeper clays. In situations of this sort, the engineer, when adequately forewarned, can resort to deeper sampling, where he may find important differences in soil strength.

The geologist is inclined to wonder whether some examples of recent earth movement are not perhaps due more to the consolidation of clays than to tectonic disturbances. The recently reported findings of a Roman city many fathoms beneath the surface of the Mediterranean, just off the mouth of the Rhône River in France, may be an example of the extreme consolidation of thick, soft deltaic deposits rather than a case of crustal subsidence of the area.

(3) The geologist can study the granular characteristics of fine-grained soils, particularly clays, and correlate his observations with data on mechanical behavior. The mineralogy of clays, the intergranular structure of clays, and the physicochemical characteristics of clays are frontiers of research which will in time yield information of the greatest usefulness to soil mechanics.

It is well known that the shape of sand and silt grains affects to some extent permeability, internal friction, and even the elastic properties of soils. The intergranular structural arrangements of clay crystals are only imperfectly understood, although it is known that they have an important effect on strength. What are the formational environments, and what clay minerals produce the different cellular and flocculated arrangements of clay crystals? The mortar structure of many clays, that is, a structure characterized by an open skeleton of large non-clay mineral grains embedded in a matrix of clay minerals, may produce hybrid mechanical properties. Frictional strength may be imparted to the soil by the non-clay framework. A shifting of the contact points of these grains may suddenly destroy the strength of the framework, and a weakening of the whole clay mass may result.

The chemical activity of the clay minerals is known to affect permeability and plasticity. The permeability of montmorillonite clays has been reduced by introducing sodium ions into a calcium-rich clay. A famous example of this was the treatment of the clay lining of the lagoon on Treasure Island for the 1939 Golden Gate Fair in San Francisco (Lee, 1940).

The surface activity of clay minerals affects strength and permeability. Plasticity is an index property of primary importance. Highly plastic clays almost always bring with them difficult engineering problems. The nature of all the factors affecting the plasticity and the cohesion of clays is yet to be determined. Is the theory of the adsorbed water layer on the surface of the colloidal clay crystals the only and entire explanation of cohesion, or will further research suggest other forces?

The correlation of plasticity data, as expressed by the Atterberg limits, with geological observations may be of far-reaching consequence in furthering knowledge of the mechanical properties of clays. Geologists will do well to recognize that plasticity is a property as important to study in cohesive soils as are grain size, rounding, and mineral content in the study of sands.

The loss of the cohesive bond of many clays on disturbance and manipulation and the slow redevelopment of cohesion on standing (thixotropy) is a soil property concerning which are many questions. There are a number of examples of the practical importance of this property. For example, the movement of a large soil mass on the shores of Lake Gerzen, Switzerland, was brought about by the weakening of the cohesive bond of a lake marl due to the vibrations set up by the blasting of the stumps of trees (von Moos and Rutsch, 1945).

The phenomenon of the movement of pore water in soil under electric and thermal impulses has led to a number of attempts in recent years to drain and stabilize soils by electrical methods. Although it is widely believed that this is essentially a phenomenon of the electric double layer, or the charged layer of oriented water molecules on granular surfaces previously mentioned in connection with plasticity, there is still need for additional investigation into the cause of electro- and thermo-osmosis before large-scale application becomes practicable.

The list of questions on fundamental soil properties is long, and the solution of any of them would undoubtedly be of value to both soil mechanics and geology. In the field of applied soil mechanics there is no reason to advocate that geologists should, or even could, replace engineers in the purely engineering application of soil mechanics. The geologist's role will probably continue to be that of a consultant on engineering matters, and the final decision regarding design will undoubtedly always remain the engineer's responsibility. Greater awareness, however, of geologists of the utility of soil mechanics would result in the training of more geologists able to answer in a quantitative way not only the engineer's quantitative questions on soils, but also some of geology's quantitative questions on earth materials.

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Chapter 6

SEDIMENTATION AND GROUND WATER *

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Ground water is the water that occurs below the surface of the earth in the zone of saturation. Few, if any, places on the earth are devoid of ground water, though the quantity of it may be small. In most places it is sufficiently plentiful to form all or an important part of the water used by man to sustain life, and in many areas there is enough to operate industry or irrigate crops. The location, development, and distribution of ground water is a major industry. In the United States the total amount of ground water used in 1945 was about 20 billion gallons a day, nearly double the amount used in 1935 (Sayre, 1948).

The almost universal occurrence of ground water in the crust of the earth makes it an element, either beneficial or detrimental, to be considered in almost all engineering construction projects, in mining, and in petroleum production. It may have to be drained, pumped, or walled out at considerable cost to permit construction or to allow operation of projects. Disposal of oil-field brines also is a serious problem in some areas. Ground water has played an essential role in the deposition of many ore deposits.

The occurrence and recovery of ground water for beneficial use will be discussed in this chapter, rather than its significance in other activities.

OCCURRENCE OF GROUND WATER

Though ground water in usable quantities may be found in any kind of rock in which openings occur of sufficient size and continuity to allow its passage, by far the most prolific aquifers are certain types of sediments, especially stream-laid sands and gravels and cavernous limestones. Volcanic rocks of the Columbia Plateau, the Hawaiian

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Islands, and some other parts of the world are sources of large quantities of ground water. Weathered and fractured metamorphic rocks in some areas are the only source of ground water, as, for example, in parts of New England and the Piedmont Plateau of the southeastern United States, but the quantities of water obtained from them are small and sufficient usually for only small individual domestic supplies. Intrusive igneous rocks also generally yield only small supplies.

As the sediments are the most important of all rock types as reservoirs from which ground water may be extracted, knowledge of their classification, origin, and transportation is essential for the practical development of most ground-water supplies.

WATER-YIELDING CAPACITY OF SEDIMENTS

To be of practical importance as a water-bearing formation, or more properly a water-yielding formation, or aquifer, the material must be of such a character that water can move through it rapidly enough to furnish water to a well or spring. The amount of water that a sediment contains when saturated is the same as its porosity, usually expressed as a percentage by volume of the total volume of the rock. The amount of water, also expressed as a percentage of the total volume, that the sediment will yield by gravity drainage is the specific yield of the material; that retained by the material is its specific retention. Estimates of supplies available in any formation based only on porosity, without consideration of specific yield, are likely to be entirely wrong. A thorough discussion of principles of the water-yielding capacity of rock materials is given by Meinzer (1923).

PERMEABILITY

The permeability of a rock or soil with respect to water is its ability to transmit water under pressure. Darcy (1856) verified the earlier work of Hagen and Poiseuille, in which they demonstrated that the rate of flow of water through capillary tubes is proportional to the hydraulic gradient and showed its applicability to permeable filter sands. The principle is stated as Darcy's law and is sometimes expressed as

$$Q = PIA$$

in which Q is the quantity of water discharged in a unit of time, P is a constant which depends on the character of the material, I is the hydraulic gradient, and A is the cross-sectional area through which the water passes. The constant P is usually called the coefficient of permeability. It has been expressed in various units by many investigators. The coefficient of permeability used by the U. S. Geological Survey was defined by Meinzer, who selected gallon, day, and square foot as the units most applicable to ground-water work. Meinzer's coefficient is the rate of flow of water, in gallons a day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 percent at a temperature of 60° F. It is adapted for field use by correcting for the prevailing temperature of the ground water in the area under study. Wenzel (1942, p. 11) lists ten different permeability units in use in the United States and conversion factors for changing these units into Meinzer's units, or Meinzer's units into these units.

The term "coefficient of transmissibility" was introduced by Theis (1935, pp. 519–524) and is now in common use in water-supply work. It is Meinzer's field coefficient of permeability multiplied by the saturated thickness of the aquifer, and it is particularly useful because it describes the ability of an aquifer as a whole to transmit water, an essential factor in determining the actual amount of water that can be obtained from an aquifer. It is also readily determined from data collected during pumping tests.

Permeability of Sediments

The permeability of the sediments ranges from extremely low for clay, the most nearly impermeable sediment as a source of water supply, to very high for coarse, clean gravel and cavernous limestone, the most productive of all aquifers. Clay is useless as an aquifer not because it contains no water, for many clays have a porosity of more than 50 percent and are saturated with water, but because the interstices between the grains are so small that essentially all the water is held tightly by molecular attraction.

Permeability of a sediment depends not only on the absolute size of the constituent grains, but also on the sorting of the grains. A clean, fine-grained sand may have a higher permeability than a coarse sand or gravel in which the spaces between the larger grains are filled with finer material.

Coefficients of permeability have been determined in the hydrologic laboratory of the U. S. Geological Survey on many hundreds of samples of material from many states. Ten samples are listed in Table 1 to illustrate the relation between grain size, sorting, and permeability. The table includes the highest and lowest coefficients determined so far in the hydrologic laboratory, but undoubtedly other materials exist with higher and lower coefficients.

TABLE 1

RELATION OF GRAIN SIZE TO PERMEABILITY

Laboratory No.	Size of Grain (Percent by Weight)								Apparent Specific Gravity	Porosity %	Coefficient of Permeability (gal. per day per sq. ft.)
	Larger than 2.0 mm.	2.0–1.0 mm.	1.0–0.5 mm.	0.5–0.25 mm.	0.25–0.125 mm.	0.125–0.062 mm.	0.062–0.005 mm.	Smaller than 0.005 mm.			
1,001	....	0.6	1.0	3.0	5.7	24.7	44.0	21.0	1.62	58.2	0.0002
2,278	....	....	....	2.5	0.9	1.0	45.3	49.3	1.20	55.5	0.2
2,286	19.6	24.2	17.4	25.9	8.8	1.3	1.5[1]	....	1.54	37.0	30
1,382	15.4	15.2	20.2	19.5	16.4	7.0	4.5	1.5	1.92	26.3	150
1,374	29.7	16.9	18.9	17.1	15.4	1.3	0.4	0.2	1.90	27.1	480
1,562	17.9	31.4	32.2	14.0	2.0	0.8	0.4[1]	....	1.63	31.4	1,200
1,393	40.4	15.5	22.8	16.5	3.9	0.4	0.3	0.1	1.87	27.2	2,600
2,325	75.2	8.6	9.4	5.2	0.7	0.2	0.2[1]	....	2.06	23.4	4,200
1,564	68.2	14.8	11.8	4.2	0.4	0.1	0.2[1]	....	1.86	25.6	12,800
2,241	90.0	7.9	1.0	1.0	0.1	0.1	0.1[1]	....	....	38.0	90,000

[1] Includes clay.

It is apparent from the table that, in general, the coarser grained materials are more permeable than those with predominantly finer grain. The table also shows that the proportion of large grains alone is not necessarily significant, but that samples having a higher proportion of small sizes generally have lower permeability.

Wenzel (1942, pp. 21–50) lists a comprehensive bibliography on permeability and laminar flow prepared by V. C. Fishel.

The water-bearing properties of various rock types are not described in detail in this chapter, and the reader is referred especially to Meinzer (1923, pp. 117–148) for detailed descriptions.

Special mention should be made of the limestones and associated rocks as aquifers. Though normally they are compact fine-grained rocks, they are excellent aquifers in many places where extensive openings have been produced by fracturing and solution. The capacity of the limestones and associated rocks to produce water is likely to be erratic even within a small area, for if a well does not happen to encounter many or large fractures or solution channels it will have a small capacity. Because of the continuous character of most of the openings, the water from limestone formations is much more subject to pollution than is the water that moves through the interstices between grains, as in sand and gravel.

GROUND-WATER STUDIES

The study of the ground-water resources of any area is fundamentally geologic. Extraction of ground water after it has been located is dependent upon the character and attitude of the rock formations that contain it, and upon the climate and opportunity for recharge. As the sediments are the most important of all rocks as aquifers, the sedimentary processes that produced the aquifers are of prime significance.

The first step in examination of ground-water resources of an area is to map the geology and to become familiar with the kinds of materials to be found. The stratigraphy of the whole section must be studied, with special emphasis on the possible aquifers. Study of the outcrops of aquifers is especially important in relation to recharge, because outcrop areas are the places where the water enters to replenish that which is withdrawn. Possible impermeable cover that might seal the recharge areas is important. For example, relatively impermeable glacial till impedes recharge in parts of the Cambrian sandstone aquifers that supply the artesian water in eastern Wisconsin. Impermeable strata also act as barriers which confine water under artesian pressure, or they may cause the water to emerge as springs by preventing downward movement of ground water, thus forcing it to move laterally.

Indispensable tools in water-supply studies are well logs. Accurate logs can be obtained only by examination of drill cuttings, where identification of sedimentary materials and their stratigraphic location for correlation must be made, but electrical logs are useful as an aid. The U. S. Geological Survey and most of the state geological surveys maintain files of carefully identified samples of cuttings from water wells. They form an invaluable source of information for determining the character of the formations, both aquifers and non-aquifers; for choosing the best locations for new wells and for estimating probable yields of water from them; for forecasting the type of well construction that will be most satisfactory in the area; and for pointing out probable difficulties that may arise during well construction.

Methods for the quantitative examination of water resources have been developed and improved greatly during the past fifteen years. Basic mathematical concepts of the nature of the movement of water through permeable materials are analogous to the transfer of heat through a homogeneous medium (Theis, 1935). No natural aquifer is isotropic; therefore corrections, determined from the examination and evaluation of the sedimentary characteristics of the material, must be made to compensate for departures of the actual aquifer from the ideal isotropic aquifer. Grain sizes and sorting vary, both parallel to and normal to bedding planes. No standard method of applying corrections can be set up because each area has its own characteristics, and at the present time the effect of sedimentary changes in aquifers on transmissibility is not easy to evaluate. Research needs to be continued in many areas where detailed quantitative studies are in progress to determine the effects on transmissibility of such changes in lithology.

WELL DRILLING AND DEVELOPMENT

The consulting engineer and the well driller are continually encountering problems in sedimentation during well construction and development. There are few places where wells can be drilled where there is not at least one of the problems of caving walls, quicksand, or water-bearing material that must be screened out or retained with a gravel wall and then properly developed (Bennison, 1947). A thorough knowledge of the sediments and careful examination of them as drilling progresses can prevent much grief and, by indicating proper drilling and development methods, may make the difference between a poor well and a good one. The selection of the proper screen for a well in formations where influx of sand must be inhibited requires a careful sieve analysis of the material of the aquifer. The best screen size seems to be one that will allow the finer grains near the screen to pass through during development of the well, leaving the coarser grains outside. This process increases the permeability of the aquifer near the screen and increases the well capacity. If an artificially gravel-walled well is to be constructed, the same careful analysis is necessary to select the ideal gravel size or sizes that will retain the aquifer material and yet allow maximum flow of water to the well.

SEDIMENTS OF VARIOUS ENVIRONMENTS AS SOURCES OF GROUND WATER

In the following description of sediments of various environments and their importance as sources of ground water, Twenhofel's classification (1932, pp. 785–871) has been followed in general. Sedimentary deposits of almost all environments are sources of ground water, some much more important than others. The younger sediments are usually more prolific in yield, because cementation has not progressed so far; thus they commonly have a relatively higher permeability. However, some pre-Cambrian sandstones are usable aquifers; for example, late pre-Cambrian sandstones in the Lake Superior district of northern Wisconsin yield water to wells in several places, though some of the water is highly mineralized. The Paleozoic sediments of the Central States area are important aquifers, and in places some beds of sandstone are almost completely uncemented.

CONTINENTAL ENVIRONMENTS—TERRESTRIAL

The Desert Environment

True desert deposits play a part in the water supply of desert areas. Wind-blown sand may be a source of usable ground water. Desert sediments in the United States are usually intermingled with piedmont deposits and are not readily distinguished from them. The saline deposits of the desert environment cause the ground water in many places to be highly mineralized and so are a detriment to development of ground-water supplies.

The Glacial Environment

Deposits of glacial origin are very important sources of ground water, and in some areas the only source. Though the good aquifers are water-sorted, and so are fluvial, they are normally considered to be of glacial origin. In glaciated areas underlain by crystalline rocks in parts of New England and in most of the North American pre-Cambrian shield area, the glacial deposits are the only source of ground water, or the only source of a sufficient quantity to supply more than small domestic wells. In much of northeastern North Dakota and northeastern Montana, the glacial deposits are the only source of ground water for municipalities and most farms.

Glacial deposits have a wide range in their capacity as aquifers. Till is so heterogeneous in its composition that normally it has a very low permeability. The gravel and sand deposits of water-sorted glacial material form some of the finest aquifers known. The large quantities of water escaping from melting ice sheets laid down extensive deposits of sand and gravel in front of advancing ice, at the edges of ice sheets, and from streams flowing on and in the ice itself. Many preglacial valleys have been filled with sand and gravel and now form excellent aquifers of great economic importance. The buried valley of the preglacial Rock River in southern Wisconsin and northern Illinois is an example. The water supply for Dayton, Ohio (Norris, 1948), is obtained from a buried preglacial valley.

Outwash plains, eskers, kames, and kame terraces all form important aquifers. The extensive outwash plains off the front of the Wisconsin end moraines in Wisconsin are good examples. In the Antigo area in northern Wisconsin the outwash plains furnish much water for municipal, domestic, and irrigation use. The problem of locating supplies of water from glacial deposits is a special field which requires a thorough knowledge of glaciology.

CONTINENTAL ENVIRONMENTS—FLUVIAL

Piedmont Environment

Some of the sediments deposited on piedmont slopes are important aquifers. In much of the basin-and-range country of the southwestern United States they, and sometimes associated desert deposits, are the only source of ground water, and frequently the only source of water of any kind.

Most piedmont sediments, however, are not good aquifers, for they are formed principally by sudden floods, which deposit large quantities of relatively coarse, blocky material, and in turn are overlain by finer sediments that clog the openings, making them relatively impermeable. Most of the good aquifers seem to be stream deposits of sand and gravel formed during times of rather quiet flow in and near the stream channels themselves. Such deposits are very heterogeneous in distribution and are difficult to correlate, even for short distances.

Many of the aquifers crop out along the upper edges of the piedmont slopes and so receive annual recharge, whereas others receive recharge by slower percolation of the water from less permeable materials surrounding them. Coarse talus material near the upper edges of the piedmont slopes may allow much water to reach the sand or gravel aquifers that transmit it toward lower areas. In most piedmont areas, ground water obtained at lower elevations is under artesian pressure, and flowing or near-flowing wells are common.

An example of ground water in piedmont areas is that in Tooele Valley, Utah, described by Thomas (1946). Many other areas in southwestern United States have been studied by the U. S. Geological Survey and its cooperating agencies and the results have been published.

The Valley-Flat Environment

Included here are sediments deposited in stream channels as well as on the flood plains of streams. The character of the sediments depends on the type of material supplied to the stream, the climatic and topographic conditions at the source, and the extent of transportation. Channel deposits usually have a higher proportion of coarse material and therefore constitute better aquifers. The deposits are usually thin, and always lenticular in cross section. If a stream is actively aggrading, aquifers of considerable extent may be formed. There are extensive sand beds, primarily of glacial-outwash origin, in the valley of the Ohio River in the vicinity of Louisville, Kentucky, where large supplies of water are pumped daily (Rorabaugh, 1948). Much water is pumped from valley-flat deposits of the Platte River in Nebraska, Wyoming, and Colorado.

The very extensive Tertiary deposits of western Nebraska, North and South Dakota, eastern Montana and Wyoming, and western Kansas are good examples of valley-flat sediments. They contain much permeable material, particularly that close to the mountain fronts, and they form good aquifers in many places. At some distance from the mountain sources of material, much clay is interbedded with sand and, though the sands yield some water, the permeability is usually rather low.

CONTINENTAL ENVIRONMENTS—SWAMP

The Swamp Environment

Swamp sediments are usually poor aquifers, for the materials are generally fine-grained. Peat and coal beds may be permeable. Lignite beds in western North and South Dakota and eastern Montana provide water to many wells. The water is usually colored brown and in many places is rather highly mineralized. Coal beds provide water for many wells and springs in Pennsylvania.

MIXED CONTINENTAL AND MARINE ENVIRONMENTS

The Littoral Environment

Sediments of the littoral zone have a wide range in composition—from shale or limestone to boulder deposits. It is usually unnecessary to distinguish aquifers of littoral origin from marine sediments as sources of ground water, because they are of limited extent, particularly at right angles to the shore line. In some places, however, recognition of their origin may be significant in their evaluation as water-bearing beds.

The Delta Environment

Delta deposits are extremely heterogeneous, with great ranges in composition within short distances, both vertically and horizontally. Sediments are generally rather fine-grained and consist of sand, silt, clay, and vegetable matter. Where sand has been deposited, deltas are important sources of ground water. Delta deposits of existing streams are likely to have good recharge from the stream itself. Delta plains constitute large areas of the earth's surface at present, and many of them are densely populated. The deltas of the Ganges, Bramaputra, Nile, Hoang Ho, Rhine, and Mississippi rivers are examples of large, heavily populated deltas where ground water is obtained in large quantities and has been one of the factors in the development of the areas.

MARINE ENVIRONMENTS

The widespread, relatively uniform marine sediments are the most extensive and continuous of all aquifers in areas where they have not been disturbed by faulting and folding. The great area of Paleozoic marine sediments of the Central States contains many very important aquifers. The Cambrian sandstones of eastern and southern Wisconsin, Illinois, and Iowa provide water to wells in large quantity. A well in Madison, Wisconsin, with 240 feet of screen in Cambrian sandstone, produced more than 3,000 gallons a minute of water of excellent quality. Most of the municipalities in the area underlain by this water-bearing bed depend entirely on it for water supply.

The St. Peter sandstone of Ordovician age has long been famous as an aquifer in the North Central States, but ground water attributed to it in some places probably actually comes from other formations. The St. Peter is a poorer aquifer in Illinois than in Wisconsin, apparently owing to an increase in fine material in the sand at greater distances from the Wisconsin arch, in the core of which pre-Cambrian rocks are now exposed.

The permeability of the Cambrian sandstones in Wisconsin varies from area to area but has proved to be surprisingly uniform over distances of 20 miles, as shown in the results of pumping tests conducted in the Milwaukee-Waukesha area, Wisconsin (Drescher, 1948).

Marine limestones, where they have become cavernous as a result of solution, are among the world's most productive aquifers. The Eocene Ocala limestone of Florida and Georgia yields many millions of gallons of water daily to wells and springs (Stringfield, 1936). Limestone of Pliocene age in southeastern Florida has an average transmissibility in the Miami area exceeding 2 million gallons a day per square foot (Parker, Ferguson, and Love, 1944). The Tertiary limestones of Puerto Rico are capable in some places of yielding several thousand gallons a minute to individual wells (McGuinness, 1948).

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Part 2

ENGINEERING PROBLEMS INVOLVING STRENGTH OF SEDIMENTS

Chapter 7

SEDIMENTATION AND HIGHWAY ENGINEERING

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A knowledge of sediments, whether they be unconsolidated strata or bedrock, can be vital to successful highway construction. The science of soil mechanics in which the physical characteristics of soils are studied, measured, and evaluated has already achieved signal success in helping the engineer toward better construction. The geologists, as a whole, have not as yet made the fundamental contributions of which they are capable.

Soil and sedimentary rock origin, age, mineralogic composition, degree of weathering, and attitude in the earth's crust are all functions of the physical characteristics observed by the soils engineer. The sedimentary processes and natural or artificial agents which have brought the sediments into the position where the engineer finds them afford logical explanations for the non-isotropic characteristics of those soils and rock strata. The density, layering, intertonguing, porosity, permeability, and similar features of soils and sedimentary rock are directly related to the processes responsible for their origin and placement.

The physiographic history of an area is fundamental to an understanding of the general physical characteristics of the recent overburden and often of the configuration of the bedrock profile.

A knowledge of structural geology prepares the geologist for interpretations of the effects of joints, faults, inclined strata with their infinite variations, weathered zones, and similar features with respect to the structures placed above, or excavations made in, them.

A petrographic study involving X-ray and differential thermal analysis will determine whether the clay in a cut is the dangerous montmorillonite, or the petrographic study alone will determine whether the stream gravel or bedrock selected for aggregate has deleterious reaction in the presence of high-alkali cement.

The applications of seismology and electrical resistivity methods for determining the depth to bedrock, and the position of the water table, when used in conjunction with check core borings, speed up preliminary subsurface surveys and reduce the guesswork in estimating common and rock excavation.

Through the utilization of these and other methods, and upon the basis of geological understanding, the geologist can determine the position of bedrock, the ground-water table, subsurface divides, possible perched ground water, and can fairly appraise the nature of the underlying materials.

Because the modern major highway is planned for the purpose of satisfying the principal traffic needs of an area, and because of the advent of modern excavation and earth-moving equipment, it is now mandatory to construct roads with gentler grades and straighter alignment than ever before. In general, regional alignment is fixed for the modern high-speed highway, and only very minor local adjustments may be made. This means that, locally, sections must be built through terrain, often with undesirable physical characteristics such as swampy ground, mine subsidence areas, heavy cuts, and poor aggregates. Nevertheless, within the economic limits controlling the enterprise the project must be built as laid out.

The problems in the Appalachians are different from those on the West Coast, in the tropics or in the Arctic. It would be impossible to treat adequately the significant sedimentation characteristics of soils alone for such varied areas, yet an attempt will be made to outline some of the applications of sedimentation as they affect construction on and in the soil cover and sedimentary rock. Brief reference will also be made to slides and areas of subsidience in the hope that some of the lessons learned in recent years may be helpful to others.

CONSTRUCTION ON SOILS

In highway or airfield construction, soil is the overburden to the engineer, and he is less concerned with its origin and classification than he is with the equipment he can use to move it most efficiently and cheaply. The soils studies for airfields have, in general, been much more thorough than those for highways, but the time has come when equally careful studies of the soils must be made for roads. This applies specifically to the subgrade and the placing of base courses beneath the surfacing of modern superhighways. It follows naturally that the soils engineer will do a better job of interpreting his tests if he knows whether he is dealing with residual, fluvial, lacustrine, glacial, or some other type of soil.

There is no general agreement relative to the classification and identification of soils; hence no common usage of terms and their meanings exists. Soils may be residual or transported. If the former, they may be mature or immature; if the latter, they may be fluvial, lacustrine, eolian, volcanic, or glacial. In each of the various types there are infinite variations and rarely any approach to homogeneity. Jenny (1941) says that the soil is a physical system consisting of various properties that are functionally related. This relationship may be expressed as *soil-function* (climate, organisms, topography, parent material, time). Any one of the properties of a soil, porosity, density, etc., is determined by the independent variables listed in the parentheses. When one establishes and evaluates the independent variables, the soil type is fixed. However, by the very nature of their origin, there can be no single set of physical constants for any sedimentary deposit. A sample taken and tested from a layer located between bedding planes gives no hint of the weakness in a sample which includes the bedding plane. In an alluvial fan, glacial deposit, beach, delta, and many other types of deposits, the intertonguing, crossbedding, variable laminae, grain-size variability, mixing, and the infinite variations and successions of materials of different densities, porosities, and permeabilities make a *typical sample* a figment of the imagination. Continuous sampling and extremely close spacing of borings such as to show the true physical characteristics would not be an economic feasibility. Even then the weakest layer would be the determining factor governing the settlement of a fill or any superposed structure.

In spite of these apparent unsolvable obstacles, the soils-testing program is extremely important, and it certainly can and does indicate the direction that construction in and on soils must take. It must not be forgotten, however, that geologic factors associated with original deposition and, perchance, features located far beneath the tested zones may govern the permanent stability of a fill, foundation, or cut slope.

Residual Soils

These vary from a few inches to many feet in thickness. They also vary in accordance with the nature of the parent rock, the slope, and the weathering processes acting on the bedrock. The types of processes involved in the formation of residual soils do not evoke the concern of the engineer, but end products do. Irrespective of whether the material acted upon is bedrock or a transported soil, the residual products that remain after weathering are very important. The principal end product is clay, and the clay minerals may be divided into three groups: montmorillonites, kaolinites, and illites (also called hydrous micas and bravisites) (Grim, 1942). In illites and montmorillonites a portion of the aluminum is replaced with iron, magnesium, or both. Potassium is an important element of the illites, which are thought to be the result of alterations occurring on the sea floor rather than after uplift above sea level. The montmorillonites and kaolinites are products of subaerial weathering but also may be produced by the action of hot solutions. The importance of determining which clay may be present is indicated in one respect by the characteristic tendency of montmorillonites to swell. Consequently the identity of a clay underlying a structure or a fill should be ascertained. If ordinary soil mechanics and petrographic methods do not suffice, the sample should be submitted to the geological clay specialist for identification.

The depth to which weathering may penetrate in the formation of residual soils depends on many factors, but the principal one is time. In recent glacial deposits the effects of weathering may be negligible, but in the humid tropics it may extend to depths of 100 feet or more. It may be unusually deep along joints and faults in the bedrock.

The structural attitude of the bedrock may profoundly affect, and cause extreme variations in, a residual soil cover. In flat-lying strata, if it is assumed that secondary structures and surface conditions exert no local control, the thickness of the overburden in a section may be more or less constant. A concentration of vertical joints, or even a single joint, may allow a "seamy" condition to develop. In a limestone, this can be serious inasmuch as these weathered joint areas, filled with residuum, may be from inches to many feet in width and can appreciably increase the costs of excavation. In steeply inclined strata, similar irregularities may exist.

A series of limestone beds, steeply dipping, may have layers differing greatly in solubility. Hence it is no uncommon condition to find limestone cropping out under one wing wall of a bridge, but at a depth of many feet under the adjacent wing wall. Recent electrical resistivity exploration in Cumberland County, Pennsylvania, checked by borings and later proved by excavation, showed beneath a single bridge abutment overburden thicknesses varying from 2 to 46 feet. Such irregularities proved to be the rule in this area and were attributable solely to the solubility of individual limestone beds often only a few feet thick.

Similar conditions were found in road sections crossing steeply dipping Triassic strata. The extremes, however, were not so great because the series of strata consisted of clay shales, sandstones, and conglomerates. In this area some of the sandstones were most strongly influenced because of the solubility of the cementing material between the sand grains.

In an area of sparse surface outcrops, a contractor must gamble in estimating the percentage of common and rock excavation, but a careful geological study of the area and intelligent interpretation of the subsurface findings can reduce the gamble to a negligible factor and, in consequence, the contract bid price.

The variations in the physical characteristics of most transported soils may be extreme in both horizontal and vertical section. They are most significant in glacial deposits, alluvial fans, deltas, terraces, and beach deposits, but they may be less serious in eolian, flood-plain, lake-bed or deeper marine deposits. The rapid variations in the depositional features and physical characteristics of these sediments introduce many complications involving moisture content, density, porosity, permeability, and, ultimately, in bearing values. The many combinations embrace too many factors for detailing in this brief discussion. Nevertheless, an identification of the soil type and its origin in advance of construction eliminates many possibilities and permits intelligent analysis of those known to be associated with the particular soil types concerned.

CONSTRUCTION ON SEDIMENTARY ROCKS

The principal sedimentary rocks may be divided into those mechanically deposited and those chemically or biochemically deposited (U. S. Bur. Reclamation, 1942).

MECHANICALLY DEPOSITED

- Shale (consolidated clay)
- Siltstone (consolidated silt)
- Sandstone (consolidated sand)
- Conglomerate (consolidated gravel or cobbles, rounded)
- Breccia (angular fragments)

CHEMICALLY OR BIOCHEMICALLY DEPOSITED

(*A*) Calcareous
- Limestone ($CaCO_3$)
- Dolomite ($CaCO_3 \cdot MgCO_3$)
- Marl (calcareous shale)
- Caliche (calcareous soil)
- Coquina (shell limestone)

(*B*) Siliceous
- Chert
- Flint
- Agate
- Opal
- Chalcedony

(*C*) Others
- Coal, phosphate, salines, etc.

The ability to handle rock strata without the use of explosives depends on the physical characteristics and structural attitude of the layers. In the Appalachian region most sedimentary rock must be drilled and blasted. Exceptions are flat-lying coals and some shales and siltstones. These may often be loosened with a rooter and subsequently removed by carryall scrapers or elevating graders. In the shales and siltstones, the fissility of the rock and its horizontal position determine whether or not explosives are necessary. Many clay shales which must be blasted when initially encountered become dehydrated so rapidly on exposure that they must be treated as soils shortly after uncovering or removal from their original sites. Many Cenozoic strata are so weakly cemented that they too may be excavated with conventional road-building equipment.

Aside from drainage, slides, and subsidence problems, the chief questions relative to sedimentary rocks involve the design of cut slopes. Until relatively recent years and the advent of modern excavation and earth-moving equipment, highways utilizing deep cuts in order to minimize grades were not practical. However, with the availability of such equipment and because of the tremendous demand made on roads by modern truck transportation, the excavation of deep cuts has become a necessity.

The design of cuts depends mainly on the physical characteristics and structural attitude of the soil or rock to be excavated. Relative to soils, Terzaghi (1929) states that

> . . . the stability of all our clay fills and clay cuts depends essentially on cohesion. Due to this fundamental fact, the factor of safety of slopes with a given inclination rapidly decreases beyond the critical height at which the soil can stand with a vertical face. Hence a stable fill of a certain height and consisting of a certain clay soil is no indication of stability in a fill of twice that height, with the same slope and consisting of the same material. In computing the factor of safety of a cut or fill, the curvature of the sliding surface must be taken into account, else the results of the computation may be very misleading.

There does not appear to be, and may never be, sufficient empirical data to omit the advantages to be gained by soil mechanics testing of soils in proposed deep cuts. Fundamental data obtained relative to the stability of the slope in one soil cut may not apply to another adjacent to it because of the vagaries of normal sedimentation processes. Such vagaries are more often the rule than the exception.

In sedimentary rock cuts, even with horizontal strata, no general rule applies. Nevertheless, in massive-bedded, strongly cemented, horizontal sandstones, limestones, and dolomites, of generally homogenous materials and free from closely spaced, steeply inclined fractures and joints, slopes of $\frac{1}{4}$ to 1 and even vertical are possible. In the Appalachians the strata are seldom devoid of joints; consequently in cuts 80 or 90 feet deep and deeper there is a growing tendency to excavate benches at varying heights above grade.

The Clear Ridge Cut, near Everett on the Pennsylvania Turnpike, is one of the deepest highway cuts in North America. Here the bedrocks are interbedded sandy shales and sandstones, striking normal to the direction of the road and dipping 53° from the horizontal. This cut is 153 feet deep, 2,600 feet long, 380 feet wide at the top, and 88 feet wide at grade. Two benches, the lower 23 feet wide and 30 feet above grade, and the upper 85 feet above grade, were provided for protective and drainage purposes. Access from the ends of the cut was provided to the benches for removal of accumulated debris. The slope from grade to the lower bench is $\frac{1}{2}$ to 1, that between the benches $\frac{3}{4}$ to 1, and above the upper bench $\frac{3}{4}$ to 1, flattening to 1 to 1 near the crest. Maintenance for falling rock fragments on the shoulders and benches has been negligible in nearly 9 years of operation.

An unusual design involves a new cut on the Turnpike's Philadelphia Extension at the western approach to the Susquehanna Bridge. Here Triassic shales and sandstones dip toward the highway at angles varying from 34° to 45° and strike at an angle about 15° from the line of the road. A slope of 1 to 1 or steeper was originally planned, but it is apparent that such a slope would progressively cut off individual layers at grade. Because weak clay shales are interbedded throughout the sequence of strata, slides were invited by such a design. Consequently the slopes are now designed to follow up the "apparent" dip on the "shingle-like" edges of the strata irrespective of whether the beds dip 34° or 45°. In this way every stratum on the slope is "toed in" below grade. A bench is planned at the top of rock about 45 feet above grade, and the 20 (plus or minus) feet of overburden will be laid back on a $1\frac{1}{2}$ to 1 slope.

In cuts excavated in more or less horizontal strata where massive-bedded hard rock is underlain by clay or soft shales, progressive deterioration of the clays and shales permits undermining and collapse of the overlying strata. This condition is accelerated when the overlying hard rock is strongly jointed. A uniform slope design is obviously an invitation to rock falls unless the slopes are extremely flat, which condition in cuts 60 feet and greater in depth may not be economically sound. Observations in western Pennsylvania indicate that a compound slope design is practicable. Here, by accident rather than by intent, one cut 90 feet high shows that relatively stable slopes were developed in nodular clays and in weak clay shales on slopes between 2 to 1 and 3 to 1. In the overlying interbedded shales and sandstones, $\frac{1}{4}$ to 1 and $\frac{1}{2}$ to 1 slopes are stable.

When sedimentary rock strata in a sidehill cut strike parallel to the cut but dip into the hillside away from the road, steep slopes are feasible. Vertical fractures and joints, on the other hand, may make it desirable to modify such slopes.

Schultz, Cleaves, and Rutledge state (in press):

. . . because experience indicates that, once started, there is no way to control deep deformational slides, the modern method of slope design is to determine the stable angle of slope in advance of excavation. It is simple to prevent the development of deformational slides by the expedient of adopting extremely flat slopes. Such practice could, however, involve the excavation of more material than if the slide were actually permitted to develop. Consequently it is essential to approach the problem from a quantitative point of view. Such a procedure involves close correlation of geology and soil mechanics.

From the standpoint of soil mechanics the stability of slopes with respect to the possible occurrence of deep deformational slides depends chiefly on the following factors: shearing strength and density of the materials in question in relationship to height and slope of the banks. Shearing strengths are determined in the laboratory, and the proper slope is found by correlating the shearing strengths of the various materials with the depth of the cut and their positions in the banks. It is obvious that weak rocks generally require flatter slopes than stronger materials.

In regions of hard sedimentary strata such as the Appalachians the following statement of these three authors does not necessarily apply, but in other areas, especially those of less strongly compacted, consolidated, and cemented Mesozoic and Cenozoic strata it may be particularly apropos.

If the rock is perfectly uniform with respect to shearing strength and density, the higher the banks the flatter the slopes required. If strong rocks are overlain by weak materials, the stable slope for the former may be found by correlating their shearing strengths with the total height of the banks (weaker materials included).

The slope for the overlying weak materials is determined in a similar manner, except that only this class of materials needs to be considered in determining the effective height of the bank.

If weak rocks are overlain by stronger rocks, the slope must be the same as for a bank of equal height composed entirely of the weaker materials, but having the same densities as the materials in question.

The above analysis takes no account of the influence of bedding planes, faults, fissures, and other geological factors. Bedding planes are zones of relative weakness and potential sliding, and it should be apparent that greater danger of sliding exists when they dip steeply toward the excavation than when the inclination is in the opposite direction. Close jointing may impair the shearing strength of an otherwise strong and competent rock. From these and numerous other examples which might be cited, it should be apparent that the influence of geology is very important. Hence the importance of correlating the results of soil mechanics studies with a detailed knowledge of geological conditions.

SLIDES

Landslides have always constituted a threat to engineering projects, and they cause great annual property damage every year. They assume greater importance in highway engineering than ever before because of the deeper cuts and excavations essential in modern construction practices. A large percentage of the literature is devoted to descriptions of slide occurrences, but relatively little embraces studies of the mechanics of slide movements and their classification.

Ladd (1927, 1928) published analyses of slides and their relationship to highways, particularly types occurring in West Virginia, Ohio, and southern Pennsylvania. He classifies these as: flow-moment slides; slope-adjustment slides; small-scale adjustment slides; structural slides; and slides involving artificial fills. In a later paper (1935) he discusses slides in relationship to railway construction. Here he sets up five major groups: (1) flows; (2) slope adjustments; (3) subsidence; (4) structural slides; (5) clay ejection from clay-filled caverns opened by cuts. Within these groups are 17 subdivisions based on material type and structural control. Ladd's descriptions and discussions of control methods are more effective than his classification.

The first distinctly scientific effort at a sound classification was made by Sharpe (1938). In this work Sharpe recognizes four principal groups, which are divided into subdivisions as follows:

1. Slow flowage
   - (*a*) Rock creep
   - (*b*) Talus creep
   - (*c*) Rock-glacier creep
   - (*d*) Soil creep
   - (*e*) Solifluction
2. Rapid flowage
   - (*a*) Earth flow
   - (*b*) Mud flow
   - (*c*) Debris avalanche
3. Sliding
   - (*a*) Slump
   - (*b*) Debris slide
   - (*c*) Debris fall
   - (*d*) Rock fall
   - (*e*) Rock slide
4. Subsidence

   Sinking over mines, caves, etc.

The general treatment is excellent, and Sharpe shows how the classification of mass movements of earth rest on variable factors such as (1) type, size, cause, and rate of movement; (2) water content; (3) type of material involved; (4) characteristics of internal friction and organization of material within the moving mass; and (5) relationship of the moving mass to surface material and substrata. The two principal types of mass movement, flows and slides, depend on the presence or absence of a slip plane. Within the limitations of a geologist who makes no claim of also being an expert in soil mechanics techniques and the mechanics of soil movement, Sharpe's work is excellent. Subsequent writers, including soil mechanics specialists, have not improved on his classification, although they have materially aided in presenting some idea of the mechanics of movement.

Terzaghi and Peck devote considerable space not only to the theory relative to stability of slopes (1948, pp. 181–191) but also to stability of hillsides and slopes in open cuts (1948, pp. 354–371). They also suggest a classification for slides based on the types of soils in which they occur: (*a*) detritus, (*b*) sand, (*c*) loess, (*d*) fairly homogeneous soft clay, (*e*) clay flows, and (*f*) stiff clays. These are analyzed on the basis of the assumption of more or less homogeneity. In two additional groups more complex types are considered: (*g*) clay with layers or pockets of water-bearing sand; and (*h*) sudden spreading on clay slopes.

They state that slides may occur slowly or suddenly, in any conceivable manner, but claim that they are usually due to excavation or to undercutting of the foot of an existing slope. Initiation of sliding may be caused by gradual disintegration of the soil, starting at hair cracks which subdivide the soil into angular fragments, or by increase of pore-water pressure in permeable layers, or by shock which liquefies the soil beneath the slope. They admit that, because of the variability of the factors and processes leading to slides, the conditions for slope stability generally defy theoretical analysis. In addition they agree that secondary structures and conditions may invalidate the results of computations.

For cohesionless dry sand, they express the slope factor of safety relative to sliding by the equation

$$G_s = \frac{\tan \phi}{\tan \beta}$$

where the angle β, made by the slope with the horizontal, is equal to or less than the angle of internal friction ϕ for loose sand.

They state that, in homogeneous, cohesive soils, material with

. . . a shearing resistance,

$$s = c + p \tan \phi$$

can stand with a vertical slope at least for a short time, provided the height of the slope is somewhat less than H_c [the critical height]. If the height of the slope is greater than H_c, the slope is not stable unless the slope angle β is less than 90°. The greater the height of the slope, the smaller must be the angle β. If the height is very great compared to H_c, the slope will fail unless the slope and β is equal to or less than ϕ.

Terzaghi and Peck say that slope failures in cohesive material are preceded by tension cracks near the top of the slope and that at some subsequent time sliding along a concave surface occurs. When the failure on this surface intersects the toe of the slope or some point above the toe, the slide is known as a *slope failure.* If failure occurs on a surface some distance below the toe of the slope, it is known as a *base failure.* In Sharpe's classification both of these types would be termed *slump.*

Terzaghi and Peck further point out that because failures of slopes are common during the construction period, such failures can be considered as large-scale shear tests, thereby offering an opportunity for evaluating minimum shearing resistance and avoidance of similar failures by a design change in further slopes in that vicinity and material (see Fig. 1).

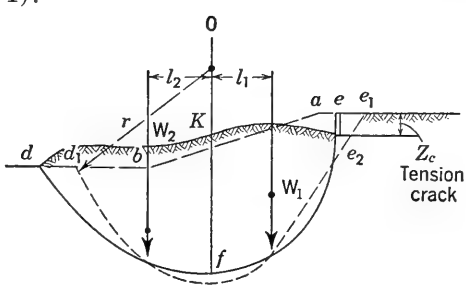

FIG. 1. Slumping due to slope failure. (After Terzaghi and Peck, 1948, p. 182.)

. . . The depth z_c of the tension cracks and the shape of the surface of sliding are determined by field measurements. The line of sliding is then replaced by the arc of a circle having a radius r and its center at O. Equilibrium requires that

$$W_1 l_1 = W_2 l_2 + sr\,\overset{\frown}{d_1 e_2}$$

from which

$$s = \frac{W_1 l_1 - W_2 l_2}{r\,\overset{\frown}{d_1 e_2}}$$

where W_1 is the weight of the slice *akfe* which tends to produce failure, and W_2 is the weight of the slice kbd_1f which tends to resist it.

For the determination of slopes with known shear characteristics the authors say:

. . . it is necessary to determine the diameter and position of the circle that represents the surface along which sliding will occur. This circle, known as the *critical circle*, must satisfy the requirement that the ratio between the moment of the forces tending to resist the slide and the moment of the forces tending to produce it must be a minimum. Hence, the investigation belongs to the category of maximum and minimum problems exemplified by Coulomb's theory . . . and the theory of passive earth pressure. . . .

After the diameter and position of the critical circle have been determined, the factor of safety G_s of the slope with respect to failure may be computed by means of the relation [see Fig. 1]

$$G_s = \frac{\text{moment of resisting forces}}{\text{moment of driving forces}} = \frac{W_2l_2 + sr\,\overset{\frown}{d_1e_2}}{W_1l_1}$$

wherein r represents the radius of the critical circle and d_1e_2 the length of the surface of sliding.

Many variations are required in accordance with data such as soil differences and position relative to the water table. The computations will serve as a guide for design in trying to ascertain probable failure. Because of the tremendous variations in soil, and soil and rock combinations, and even rock slides wherein the end results are similar to Sharpe's "slump" for soils, or Terzaghi and Peck's "slope failure," the engineer must not place too much confidence in either soil mechanics or purely geological interpretations alone. In such problems these specialists form a natural team whose cooperation is essential to further slide studies.

SUBSIDENCE

As defined by Sharpe (1938), "Subsidence is movement in which there is no free side and surface material is displaced vertically downward with little or no horizontal component." The causes of subsidence are varied, and their end result evokes serious concern in highway construction. Chief among the types are settlement over coal mines, compaction of unconsolidated sediments through drainage of swamp lands, solution and removal by natural or artificial means of salt, gypsum, and sulphur, depletion of oil fields, lowering of the water table through excessive public and private usage, break-through over sinkholes in limestone areas, changes in the "active" layer in regions of "permafrost," and kettle-hole subsidence in recently glaciated areas.

As problems relating to construction in "permafrost" areas are described in Chapter 14, they will not be considered here. It will suffice to say that no subsidence problems involving loss of bearing values in soils are more serious than those encountered in arctic "permafrost" regions. See Muller (1947) and Hardy (1946).

Subsidence in kettle-hole areas, because of their limited size and restricted regional distribution in glaciated areas, is of minor importance. Settlement is ascribed to melting of ice layers or lenses, insulated for long periods after general ice retreat by overlying materials. Settlement over metal mines is not uncommon, but that over coal mine areas is of serious concern to railway and road construction, especially in the eastern part of the United States. In Illinois, where the coal layers are relatively flat-lying, subsidence has usually resulted in long, gentle sags. Break-throughs to the surface are rare, but ponding in the depressed areas is common. Here compaction of the overlying sediments causes a squeezing of the water to the surface and annually results in considerable property loss, particularly in agricultural land. Structural damage to buildings occurs, and regrading of railways and highways is sometimes necessitated. Probably nowhere in the United States has more study been given to this problem than in Illinois; see Rice (1940), Cady (1921), Herbert and Rutledge (1927), and Young and Stolk (1916).

In Pennsylvania, cave-ins in the anthracite areas, where whole buildings and even sections of roads drop into the steeply dipping mine workings, are common. The bituminous coal fields in the same state have not caused such catastrophic conditions; nevertheless mine settlement areas and cave-ins have resulted in various construction safety measures. In the Pittsburgh region special grouting techniques have been developed to afford safety for major building construction. Not only are void areas present in the form of open rooms and galleries, but also in areas of total roof collapse and in "mine-gobbed" sections and in the cracked zones above settlement sections, different techniques, grout mixes, and variations in dry "slushing" are successfully used. In the line of the original Pennsylvania Turnpike, where mined-out coals showed pitted cave-in areas, it was the practice to remove the coal, pillars, gobbed rooms, and collapsed roof debris to the full width of the highway and backfill with suitable material. The depth to which excavation extended rarely exceeded 40 feet. Galleries outside the line of the roadway were bratticed off, and, when necessary, transverse drains permitting the original mine drainage to function were installed. A number of bridges were also located in these areas, and their foundation excavations were carried beneath the former mine workings and beneath the underclay when it was present. No subsidence has occurred under any of these structures where such work was carried out. Where the coal underlay the highway at depths greater than 40 feet, the coal beneath the right-of-way was reserved, and the wisdom of such practice was observed when in one stretch coal at a depth of over 100 feet was permitted to be removed. As a result, serious damage to an underpass and substantial settlement of the road resulted within a few months.

In one small mine beneath the highway, dry "slushing" was resorted to. Here the areas beyond the road berms were bratticed off and the confined area filled with agricultural slag which was blown into position by compressed air. Sand, when available, may be handled in the same manner.

Anticipated subsidence beneath the piers of an important railway structure in the Middle West was taken care of in a similar manner. The mined-out sections 165 feet beneath the viaduct were bratticed off outside the calculated limits of the angle of draw, and an 8-inch well-drilled hole was driven from the surface into the critical area. Hoses were led down this cased hole, and lean cement grout was placed in the danger area, completely filling it. Sand or agricultural slag would have accomplished the filling as well and would have been cheaper.

Sinkhole regions present a serious problem when highways must pass above them. In country where the limestones are relatively flat-lying or massively bedded, it may be necessary to skirt such features where major caverns occur. However, in many areas the sinks are of limited extent, sometimes having considerable lineal extent in response to bedding or major joint direction, but limited lateral extent. In these, filling with field stone to preserve the natural subsurface drainage and topping off with graduated stone and soils in the road's base courses may be sufficient. In such a case a reinforced-concrete slab gives added security. Nevertheless, in some places actual bridging of sinks may be required. The most serious conditions develop when the overburden of soils conceals the cavernous condition and construction proceeds with no anticipation of the cave-ins likely to occur later. It is possible, when such caverns are relatively large, that an electrical resistivity survey would accurately determine the position of them.

Compaction of sediments is due to an assortment of causes, but common ones are drainage of swamp and marsh lands and the construction of fills on such ground. The same results arise from lowering of the ground-water table by natural causes or from excessive domestic and public usage in restricted areas. In regions of crystalline or otherwise hard rock, settlement may be negligible, but in soils and weakly cemented strata it can be a serious problem. In any area where liquids are withdrawn from the pore spaces in sediments, readjustments are inevitable and must be planned for in construction.

When marsh or swamp lands are floored by impervious material which in turn is underlain by free-draining strata, drainage by means of vertical sand drains is feasible provided that the free-draining layer is above the water table. These sand drains may be in the order of 28 inches in diameter, spaced 10 to 20 feet apart, and placed to depths of 40 or 50 feet or more (Hewes, 1942, p. 181). Sand drains of smaller diameter may be used. This method may also be used in deep soil cuts for the prevention of slides. However, when the base of the cut is close to bedrock, or the water table is high, the vertical sand drains must feed into a longitudinal drainage tunnel or into drains leading from the base of the sand drain to the gutter or longitudinal subdrains beneath the highway shoulder. Peat and organic silts, which are highly compressible, should be entirely removed when feasible, by the use of either conventional excavation equipment or explosives (du Pont de Nemours, 1939). Settlement otherwise may be anticipated, even though a prism of suitable material is used to replace the upper few feet.

Subsidence of the surface over shallow oil fields (Johnson and Pratt, 1926) or sulphur mines, where the oil or sulphur is brought to the surface in a liquid state, may cause subsidence in the form of long, gentle sags, but sometimes with offsets of a foot or two at the margins. Here, again, ponding is the chief danger, because the subsidence may be so gradual over a relatively long time that highway and railway services may not be interrupted. In extreme cases regrading may be necessary.

THE SUBGRADE AND BASE COURSES

The modern heavy-duty highway is subject to more frequent and heavier wheel loadings than ever before; hence it is essential that most critical attention be paid to the underlying soils and base courses. The soil beneath the road surface is known as the *subgrade*. *Base courses* or foundation courses are often placed between the road surface and the subgrade. The load-carrying ability of the subgrade is of vital importance, and it is often necessary to prepare these soils for the types of loads anticipated. The thickness, gradation, and other physical characteristics of the base courses are governed by the expected loadings and topographic and climatic conditions. Empirical rules accepted in the past do not necessarily apply to the modern superhighway when heavy traffic is focused on particular highways. For example: the Lincoln and William Penn highways in Pennsylvania used to share the heavy interstate trucking, but the Pennsylvania Turnpike has bled off most of this and in addition has drawn heavily on traffic from the National Highway (Route 40) and probably also the Mohawk Trail in New York. This means not only that the heaviest truck loads permissible under Pennsylvania state law use the Turnpike, but also that the frequency of their passage over any point is greater than on ordinary major highways.

The relaxation interval of the subgrade of the Pennsylvania Turnpike between loadings is probably less than for any similar route in the country. Inasmuch as this road is a forerunner of others to come, soils testing for such arteries should receive greater attention than ever before. No apt comparison is feasible between the Merritt Parkway in Connecticut, because that highway excludes truck traffic. Nor is a comparison with major airfield flight strips, because on them the traffic is far less although the wheel loadings are greater. It is apparent that the recovery time for the subgrade is longer for flight strips.

Determination of the subgrade soil characteristics is essential from the point of view of drainage and stability. These features are generally related. "Stability means, essentially, resistance to movement under conditions of moisture or load" (Hewes, 1942, p. 165). In accordance with the soil type, topographic position, climatic environment, and artificially or naturally changed conditions, the moisture content and load-bearing capacity may be extremely variable.

Hittle and Goetz (1946), investigating the factors influencing the load-carrying capacity of base-subgrade combinations, considered such variables as (1) soil type, (2) type of granular-base material, (3) depth of base material, and (4) seasonal moisture. In this study a cyclic-loading technique was developed by which measurements of the base-subgrade combinations were made and the elastic and permanent deflection characteristics of both the base and the subgrade ascertained. Their study shows that base stability is determined principally by the grading characteristics and density of the base materials.

Whereas seasonal moisture changes are of vital importance, so also are long-term climatic changes. A road constructed during a stretch of dry years may suffer serious deterioration when the cycle moves on into a period of wet years and the position of the ground-water table rises. Obviously the moisture content of the subgrade and base courses may be drastically altered and, in consequence, the associated bearing values.

Middlebrooks and Bertram (1942), in a study of soil tests relative to design of runway pavements, arrive at the tentative conclusion that, for testing the subgrade, the time-tested California bearing-ratio test is most suitable for flexible pavements and that, for determining the modulus of soil reaction and the use of this value in Westergaard's center-loading formula, the field-bearing-test method is the most satisfactory for rigid pavements. They also make a very pertinent statement to the effect that no accurate methods for evaluating the true bearing value in soils affected by frost action are known. They also state: "Highway experience indicates that, in areas which are subject to frost action the base course of non-frost heaving material under a pavement used for highway loads, should extend to a depth of at least 50 per cent of the average frost penetration, in order to provide suitable subgrade reinforcement." The most important effect of frost action is in the reduction of the bearing values of the soils.

In a critique of the above study, Campen and Smith (1942) make a point of the fact that, in laboratory testing of saturated, compacted soil samples, it should be borne in mind that soils beneath pavements are chiefly affected by moisture that reaches them from below and not through the essentially waterproof road surfacing.

The effect of steady traffic is essentially that of vibration and constant shocks which result in a densification of the underlying soils. This is less in clays, where intergranular slippage is less because of its cohesive bond, than in more granular materials. In quicksands, vibration or shock destroys the natural sand structure or bond in the surface layers and causes an upward movement of the contained pore water until the surface grains may actually be suspended, with a consequent loss in the bearing value of the sand. It is believed that a similar condition is approximated under modern high-speed highways. If there is a time lag after the passage of a heavy vehicle during which the subgrade can relax and regain the moisture "squeezed" to the surface, no permanent damage results. However, if there is not sufficient time for the soil to recover this moisture from the surficial layers, it may travel in the direction of traffic flow until it passes laterally from under the pavement or reaches a joint. If it is assumed that some of the finer particles in the base courses and subgrade move along with this moisture and are lost through "pumping" at the joints, fracturing of the pavement is inevitable. This condition is heightened during excessively wet times and is seasonal as well as cyclical over longer periods. A free-draining surficial base course which is not confined laterally by shoulder material that is too dense may provide a solution. It appears obvious that, if the soil moisture brought to the surface by constant traffic vibration cannot be recovered by the subgrade, it should be permitted egress in such a manner that the pavement is protected from permanent damage.

At the present time we do not know enough about what takes place below the road surfacing. Certainly samples taken from the shoulder at the pavement edge do not help in the understanding of changes beneath the insulated and protected part of the highway, away from the edges. A volume of case histories of surfacing failures in relationship to the thickness, sequence, gradation, and particle size of the base courses might be very illuminating. One instance is known in which under a porous surface the base courses graded from coarse to fine downward to the subgrade. The deterioration of the road with respect to bearing capacity of the surficial layers was extreme. Damage to the lower layers, however, was negligible; hence resurfacing with essentially waterproof material eventually restored this road to service.

Space does not permit expansion on the great variety of problems relative to the vast amount of qualitative data available on the subject in the literature. However, under the leadership of such original thinkers in the field of soil mechanics as Terzaghi, Casagrande, Rutledge, Taylor, and others, and with the research and quantitative data coming from the Bureau of Public Roads and the highway testing laboratories in many states, remarkable progress has been made. Constant awareness of the importance of soils testing in highway construction is essential.

FUTURE RESEARCH

The possibilities and scope of research, like the topic of sedimentation in highway construction, are of such magnitude that one can merely "brush" the surface. It goes without saying that continuing research involving soils in relationship to highway construction is necessary. Some basic work concerning slides in soils has been initiated, but the need for much more dealing with all types of dry or wet mass movements of soils, soil and rock, and rock alone in varied climatic and topographic environments is indicated.

Basic research on the bearing values of soils affected by frost action is essential if construction in the arctic and northern latitudes is to succeed. A beginning has been made, but "permafrost" studies in relationship to construction have in a sense only begun.

Additional studies of precompressed soils, such as those unloaded by erosion, exposed at the base of deep cuts, found in the beds of drained lakes and swamps, and under long-departed ice loadings, would be helpful.

Investigations of the subgrade beneath existing major highway and airstrip pavements in relationship to similar natural soils adjacent to these features might be worth while.

Refinements of geophysical exploration of soils and closer correlation between geophysical and soil mechanics investigations is necessary. Already seismic and electrical resistivity studies have proved themselves in highway construction and foundation work. In some quarters caution is indicated, because at present overly enthusiastic acceptance of electrical resistivity methods may obscure the fact that check borings are essential and it is not a single "tool" but must be used in conjunction with others.

Because of the varied topographic and climatic environments as well as the countless variations in consolidated and unconsolidated sediments of diverse origins and histories, the research possibilities are infinite. So long as men travel on or take off and land aircraft on the surface of the earth, new and continuing research will be required.

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Chapter 8

FOUNDATION PROBLEMS OF SEDIMENTARY ROCKS

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The geologic map of the United States shows the great expanse of sedimentary rocks which underlie the region from the Piedmont to the Rockies. Because igneous and metamorphic rocks appear through the sedimentary blanket only rarely, most of the major dams and many of the larger buildings in this area are founded upon sedimentary rocks. The design of these structures is influenced by the type, degree of weathering, and depth through the overburden to the sedimentary rocks. The present physical and structural properties of the rocks are influenced by their inherent geologic characteristics. Hence an understanding of the foundation problems associated with a given rock type at one locality will be of assistance in using that same rock type as a foundation elsewhere. This inferred oversimplification applies to the general problem of each rock type on which is superimposed the special problems coming from local conditions of weathering, geomorphology, geologic structure, the activities of man, and the purpose for which the rock is to be used. Although it may appear that heavy hydraulic structures impose severe requirements on foundations, it is not uncommon to find more intense local loadings developed by industrial structures and high buildings. Foundation problems may be created by such diverse causes as reversible loadings occasioned by filling and emptying of reservoirs, release of load caused by excavation, and reduction in support of the ground surface by mining. Regardless of the cause of the problem, its importance, frequency, and magnitude will be related immediately to the particular type of engineering structure and directly to the type of rock upon which the structure will be founded. It is, therefore, difficult to dissociate the problem of foundations from the implications of sedimentation. In fact, by the application of sedimentation to foundation problems of sedimentary rocks these problems are framed and reduced to more understandable terms.

Foundation problems can be reduced from numerous individual problems to two general problems the correct solution of which is paramount to the successful completion of any undertaking involving foundations. These may be phrased in many ways, but they boil down to two questions of which the first is always present and the second may be present:

(1) Will the foundation rock support the load?
(2) Will the foundation rock leak?

The answers to these questions may be automatically affirmative in rare cases, but in general the development of proved answers will require the expenditure of considerable money, effort, and thought. It is toward the reduction of these expenditures that the following remarks are directed, inasmuch as the writer believes that foundation problems can be classified rationally in relation to the type and magnitude of the structure and its geologic environment. There is a pattern in the foundation problems which he has met in the cyclic sediments of the Pennsylvanian of the Appalachian Basin, just as there is another pattern in the calcareous sediments of the Tennessee Valley, another pattern in the Permian sediments of the Mid-continent area, and another in the Cretaceous and Tertiary sediments of the upper Missouri Valley.

These comments are restricted to the rocks as we find them, without regard to the processes which developed their present characteristics, unless such processes are continuing and will affect the rocks appreciably during the lifetime of the proposed structure. This chapter considers briefly the types of foundations, the problems of determining the physical character of the foundation rock, and the problems arising from the geological character of the several types of sedimentary rocks.

FOUNDATIONS

A satisfactory foundation must support the load imposed upon it. The requirements of support may include resistance to compression, shear, sliding, and maintenance of cohesion despite repeated freezing and thawing and wetting and drying. Commonly adhesion to concrete is required. In addition to supporting properties, the foundations for hydraulic structures, such as locks and dams, must be relatively impermeable or be such that they can be feasibly and economically rendered relatively impermeable. All foundations must be insoluble during the lifetime of the project. These requirements applying to the rock mass upon which the structure is founded or abutted are stated in greater detail by Houk and Keener (1941, p. 1116).

Consider a dam. The foundation rock is under compressive forces occasioned by the mass of the structure. Shearing stresses are imposed upon the foundation by the hydrostatic head acting horizontally on the upstream side of the dam. This horizontal stress may be considered to produce a tendency to slide either on the surface of the foundation rock or on a plane of weakness at some depth within the foundation rock. A combination of shearing and sliding is usually considered in the design of gravity dams. The impermeability of the foundation is a necessity if the dam is to hold water, and yet the entire foundation from the upstream side of the dam to the toe need not be impermeable. Ideally it would be desirable if the foundation at the heel were essentially impermeable and downstream therefrom were permeable. This relationship would reduce to a minimum the area of the base of the dam on which full reservoir head could be exerted and correspondingly increase the base area subjected only to tail-water uplift. This type of foundation would permit a theoretically thinner section with consequent reduction in concrete and cost. The conditions of loading of a dam vary with the variations in the elevation of the reservoir, and the foundation rock must be sufficiently elastic to withstand these changes.

Consider a bridge pier or column footing. The foundation rock is under compressive stress, but with the flow of traffic and wind load on the bridge shearing stresses are developed in the foundation. However, it need not be impermeable, but it should be homogeneous and must be competent to support the load.

Consider a retaining wall. The foundation is subjected to the same stresses as the foundation for a dam, although the variation in stresses is greatly reduced. As in the case of a bridge pier, it need not be impermeable but it must be competent to support the load, and it is better if homogeneous.

Appraisal of Foundation

There are three methods of approaching the problem of determining safe values in bearing, shearing, sliding friction, elasticity, and permeability of a foundation: (1) experience and general practice; (2) assumption of an idealized homogeneous mass, the properties of which can be determined from extrapolation of the properties of representative samples; (3) recognition of the heterogeneity of the mass.

the physical properties of which may be indicated only within approximate limits by the physical properties of representative samples and which therefore must be considered as generally indeterminate because of the effect of geologic flaws. Regardless of the approach used, the investigation of the foundation should be continued from the planning stage through the construction stage when the foundation rock is exposed and the design assumptions can be re-examined.

Experience and general practice include all the past knowledge of foundations derived from the construction of similar structures on similar foundations. And who is to say that one foundation is the same as another? The only ones who can speak with authority are those who had intimate knowledge of the foundation upon which the past structure was built and who are as familiar with the proposed foundation. And therein lies the weakness of foundation design. One never knows as much about the foundation while it is being considered during design as one does about the same foundation during construction. However, within limits and depending upon the type and magnitude of the structure, past comparable experience and the generally considered "good practice" of the engineering profession are not to be discarded as an inapplicable approach, because they represent time-tested data. The reliability of this method is a function of the similarity of the foundations and the structures built thereon. It can be used safely only when all the data obtainable on the proposed foundation indicate values equal to, or higher than, those of the compared foundation. This is the common method used in the design of low dams on insoluble rocks, and it seems to be the method employed in fixing allowable loads on certain rocks in city building codes. It usually results in setting ultraconservative values with apparent ultimate safety factors as high as 20.

The second method is based on the assumption of an idealized homogeneous mass, the properties of which can be determined from extrapolation of the properties of representative samples. This is a typical mathematical approach to a problem, and it is beloved by the stress analyst for it yields a clean answer. But there isn't a clean answer. In the first place, sedimentary rocks are not homogeneous and isotropic. In the second place, who is to say that the samples are representative of the mass? Certainly the geologist will not say so; for he has studied the surface geology, observed the action of the core drill, logged the cores, noted the behavior of the injected water and grout during the pressure testing and test grouting, and descended the exploration shafts and pits to investigate the character and structure of the rock in place. He has seen the heterogeneity of the bedrock and the variations in rock types over the short distances between the borings. He is aware that there are variations in dips of the beds and possibly displacements along faults with resulting breccia and gouge. And what constitutes a representative sample of such a mass? Is it the almost unobtainable sample of the gouge or the easily recoverable, smooth-sided, unbroken length of solid core from the massive rock? If the properties of the massive rock are assumed to be typical of the foundation, one would feel safe in recommending high unit loads. However, if one were to recover a sample of the gouge, it would have to be subjected to the laboratory techniques of soil mechanics to obtain an idea of the highest limit of allowable unit loads. With these unit loads the logical assumption would follow that the site should be abandoned for a normal design or that a radical departure from normal design would be required with consequent increase in cost. All that is desired here is to emphasize that it would be most unusual to find a foundation of sedimentary rocks so homogeneous that the physical properties of representative samples thereof could be extrapolated to the mass foundation.

The third method recognizes that, in sedimentary rocks, foundations are composed of heterogeneous materials, the physical properties of which may be determined within limits, although in the final analysis the physical properties of the rock mass are generally indeterminate. Indications may be developed, however, which will permit limiting, rational assumptions as to the safe, allowable loadings and the reasonably anticipated rates of flow of water. Under this approach it is assumed that the presence and orientation of geologic flaws, such as planes of stratification, joints, faults, random fractures, and solution channels in distinction from inherently differing lithologic characteristics, will be compensated in the equations by safety factors. Or it may be assumed that the geologic flaws will be minimized to the extent that they may be disregarded through inclination of base of the structure, localized design to offset their effect on the mass of the structure, or specialized treatment to raise their properties to acceptable minima.

Subsurface Investigations

All three of these approaches require that the character of the foundation rocks be known, but in varying degrees. In the first case, in which the designer will rely on past experience and general practice to set the allowable loadings, there may be made little or no attempt to determine the details of geologic conditions other than to ascertain from the general geology of the area the probable rock types to be encountered in the foundations. However, it would be unusual now to attempt the design of anything other than a very minor structure without core borings. The cores would probably be no larger than a nominal 2 inches in diameter, and the logs would be based on the driller's idea of what the rock is, supplemented by the engineer's or architect's interpretation of what that means with respect to the classification in the building code or in some handbook. In general the results of this approach to loadings under small structures, and in some cases under much larger structures, has been entirely satisfactory because of the conservatism inherent in building codes and handbooks.

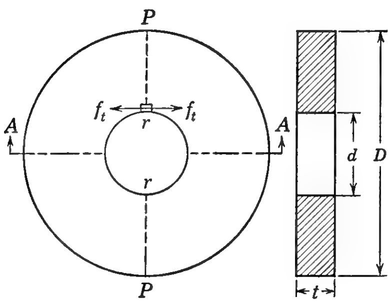
There have been sufficient examples of the unfortunate results of this approach in connection with structures of ordinary size to make it advisable and almost mandatory to consider with some care the foundation reactions under larger structures. As a result, emphasis is placed upon determining geologic conditions more clearly and exactly. Drilling tools are available with which almost 100 percent recovery can be obtained in nearly all types of sedimentary rocks. This equipment ranges from the diamond-bitted, modified standard, double-tube core barrels operated by hydraulic-feed core drills for rock drilling to ingenious soil samplers used in the sampling of unconsolidated soils and sediments. There are the large cores recovered from borings ranging from 6 inches to over 48 inches in diameter. These larger cores, formerly considered only awkward by-products of the drilling of exploration shafts, provide a source of samples for laboratory tests superior to those from smaller holes. Samples and check samples may be drilled from the large cores in the plane normal to the axis of the core, as well as parallel to the axis of the core. It would be possible to evaluate roughly the sliding friction along bedding planes with some degree of similarity to conditions underground with the use of contiguous samples of the larger cores. In other words, samples of almost any type of foundation rock can be recovered, even very soft ones.

But, the samples having been recovered, there remains the evaluation of the representativeness of these samples. In a massive foundation the samples are probably representative. But most sediments are not massive. Or, if they are massive geologically, they may not be massive in the engineering sense that the entire column of foundation rock subject to reaction to the imposed load will react as a homogeneous mass. Bedding planes in a horizontally bedded rock will affect the foundation reaction, and the closer the spacing of the bedding the more the reaction will be affected. The shear-friction factor can well be the controlling factor in the foundation design of a structure founded on horizontally bedded, average shale. In considering this factor it is necessary to obtain quantitative information on the shearing strength and sliding friction along bedding planes. If the samples obtained from the borings are approximately the lengths of the intervals between the major bedding planes, the laboratory tests will not produce these data. The samples therefore would not be representative. The criterion, then, of whether a sample is representative of foundation conditions is not whether the sample came from a given elevation in a boring in the foundation but whether that sample contains the critical element—be it structural, stratigraphic, or lithologic—which is present at that elevation.

MATERIALS TESTING

It is common practice to investigate the physical properties of the foundation materials by laboratory tests in order to obtain data to be included in the computations relating to the stability of the structure and to define the characteristics of the foundation rock. The stability calculations require the determination of the shearing and compressive strengths. It is desirable to include tests to indicate the coefficient of friction between concrete and the proposed bearing surface of the rock, as well as between rock surfaces on either side of the planes of weakness on which sliding friction may be a factor in the design. More recently there has been added to these three tests a test for the purpose of measuring the unit tensile strength of the rock. By means of this test, in conjunction with the unit compressive strength of the material, the angle of internal friction or cohesion of the rock may be calculated. Certain routine tests to determine the total absorption, specific gravity, void ratio, and porosity are primarily designed to provide quantitative data on the general characteristics of the rock. These do not enter into the calculations involving stability, but they may be used in indicating consolidation under loading or expansion with decrease in loading. A test to determine the soundness and durability of the rock, and its susceptibility to weathering when exposed, is called the weathering test and is of considerable use in indicating the relative cohesion and the necessity for protecting the rock from deterioration during the period of construction. This test also provides an indication of the reliability of the bond that may be obtained between concrete and rock. Some compaction rocks weather rapidly and in a matter of a few hours may develop a thin coating of fine, discrete particles which would form a film between the rock surface and the concrete, thus preventing the formation of a good bond between the concrete and the rock.

The shearing test consists in mounting a test specimen in two cast-iron blocks in such a manner that a single shearing load may be freely applied to the required shearing plane of the test specimen. In a core of horizontally bedded rock drilled normal to the bedding plane, a load is applied parallel to the axis of the core by means of a calibrated spring, and the load parallel to the bedding is then applied to one of the shearing blocks through a compression machine at a rate of approximately 500 pounds per square inch per minute. The test is continued until the specimen fails, and the unit shearing strength is then computed by dividing the total load by the area of the plane of failure.



P = total load

$\frac{P}{t(D-d)}$ = unit load on section A-A

f_t = unit tensile strength at r

FIG. 1. Diagrammatic sketch of ring test. (After Philippe, 1941.)

The unconfined compression test is conducted similarly to the compression test of concrete cylinders, with the load applied to the specimen at the rate of 1,000 pounds per square inch per minute. Where possible, the angle α, which the surface of the compression break makes with the horizontal, is measured, and the angle of internal friction ϕ is computed by the formula $\phi = 2(\alpha - 45)$.

Mr. R. R. Philippe (1941, p. 3), Director, Ohio River Division Laboratories, Corps of Engineers, U. S. Army, has developed a ring test for measuring the unit tensile strength of the rock.

The test consists of applying a line load to a ring specimen of the rock. The specimen is prepared by cutting a narrow section of the rock core with the cutting machine, and then finishing the cut surfaces on a lapping stone with a carborundum grain to make them true, after which a hole is drilled through the center. The rings are so proportioned that the thickness of the ring and the diameter of the drilled hole are from 10 to 15 percent of the diameter of the specimen. [The method of applying the load and the required dimensions to be measured are shown in the sketch of Fig. 1.]

The dimensions of the ring and the total load at failure allow an evaluation of the unit tensile strength which, together with the unit compressive strength of a similar material, is used to calculate the angle of internal friction and cohesion of the rock. The equations used are as follows:

By Mohr's Theory of Rupture:

$$\phi = \text{arc sin} \frac{f_c - f_t}{f_c + f_t} \tag{1}$$

$$c = \frac{f_t}{2 \cos \phi} (1 + \sin \phi) \tag{2}$$

where f_c = unit compressive strength, f_t = unit tensile strength, ϕ = angle of internal friction, c = cohesion.

Using the results from equation (1) and (2) the shearing strength s_s for any given normal load P can be computed by Coulomb's equation:

$$s_s = c + P \tan \phi \tag{3}$$

The elastic properties of the rock are determined by the standard tests of modulus of elasticity and are pertinent to the determination of the question whether or not consolidation and settlement will occur. It is common to find in sedimentary rocks greatly varying elastic properties between different rock types. At the site where a structure is to be constructed upon rocks of different elastic properties, allowance for this condition may be required in the design. This would be pertinent at a site where steeply dipping rocks strike diagonally across the site so that sections of the individual foundations would be located on different rock types. Elastic properties of the rock are also to be considered when repeated loading and unloading of the foundation occurs or when marked decrease in the loading may result from the execution of the proposed plan of construction, as, for instance, in the excavation of a spillway cut in which several hundred feet of rock may be removed and a relatively large area of concrete pavement may be constructed upon the rock thus exposed.

Safe Bearing Capacity

Philippe (1941, p. 7) has summarized the computation of bearing capacity as follows:

In computing bearing capacities from the shearing strength of a foundation material, the following formulas based on the theories of elasticity and plasticity are recommended:

(1) Theory of Elasticity:

$$p = \pi s_s \tag{4}$$

where

p = the bearing capacity
s_s = shearing strength of the material

The above formula is to be used with minimum or average shear strengths obtained from the direct shear tests. When the formula is used with values of c and ϕ, a factor of safety F of 4 is usually applied; then

$$s_s = c + p \tan \phi$$

From Equation 4

$$s_s = \frac{p}{\pi}$$

Then bearing capacity p becomes

$$p = \frac{\pi c}{F - \pi \tan \phi} \tag{5}$$

(2) Theory of Plasticity:

Using a factor of safety, $F = 4$

$$F_p = \frac{\pi}{\sqrt{3}} s_0 = 1.81 s_0 \tag{6}$$

where s_0 = the yield strength of the rock in tension.

In the above formula, the ultimate tensile strength of the rock is used for s_0. This is an allowable approximation since for brittle materials the yield strength in tension is only slightly less than the ultimate tensile strength.

The application of the preceding equations to test samples of shales indicated that allowable loads could exceed 40 tons per square foot. Existing building codes would probably rate similar shales in bearing capacities at 8 to 10 tons per square foot, indicating an apparent ultimate safety factor on the order of 16 to 20.

In analyzing the foundation reaction under masonry dams, Creager, Justin, and Hinds (1945, pp. 295–304) and Houk and Keener (1941, p. 1126) have placed emphasis on the shear-friction factor of safety. In these calculations, shear strength of the rock at the base of the dam, based on average shearing strength of that material, is included. The determination of the coefficient of friction is not usually subject to test but is assumed to be between 0.6 and 0.8.

In order to obtain the desired critical data it may be necessary to take the test to the sample and conduct a field test on the rock in place. Should the field test indicate values in the same order as the laboratory tests, it may be assumed that the laboratory tests are yielding reliable data. In actual practice, before field tests are resorted to, one of the following conditions must arise: preliminary calculations of loadings must indicate that the estimated strength of the foundation rock will be approached closely by the loadings to be produced by the proposed structure; or the strength of the foundation rock must be unknown and questioned, as in the case of certain shales upon which no comparable structures have been built. Field tests have been conducted at Possum Kingdom Dam (Niederhoff, 1940) on the Brazos River in Texas, at the location of Watts Bar Dam (Rountree, 1940, pp. 1538–1543) on the Tennessee River, and at the Lake Lynn Dam on the Cheat River in West Virginia, to mention only a few. Tests of bearing capacity, shearing and sliding strengths, and reaction to repeated loading and unloading have been performed.

Blocks of concrete are poured directly upon a surface of shale prepared as if it were to be the foundation for the project structure. Under a vertical load supplied as in a common load test on a bearing pile, the block is subjected to horizontal force by jacks. Both vertical and horizontal forces may be increased, or the horizontal force alone may be increased. Suitable instrumentation permits the recording of deformation and the applied forces. The test is continued usually until failure of the foundation is achieved either under continuously increasing load or repeated reloadings. After the failure, horizontal loading may be applied again and an indication obtained of the coefficient of friction. If the failure occurred in the rock, the coefficient will refer to the friction of rock on rock and will be of value in analyzing the rock foundation; however, if the failure occurred at the contact of the concrete and the rock, the subsequent loading will indicate the frictional value of concrete on rock. The data derived from such field tests are indicative of the conditions prevailing at the location of the test block and may be extrapolated to the remainder of the foundation area in relation to the similarity and homogeneity of the rock.

A characteristic of shales and other argillaceous sediments that is commonly overlooked in relation to foundations is the tendency to consolidate under a load less than required to produce failure. In field and laboratory testing of the less elastic shales the rate and amount of consolidation are measured in relation to time and to the increased loading. Because many structures impose varying loads, the rebound or return toward original volume is also determined with the release of loading. Cyclic loading and unloading in the range below failure may be applied until the shale approaches a degree of consolidation where effects of successive cycles are essentially those of preceding cycles.

In summation, it is a practical impossibility to define the ultimate mass strength of a foundation, although quantitative indications may be obtained of the strength of the rocks by means of field and laboratory tests (Burwell and Moneymaker, in press). It is the writer's impression that most foundations are considerably stronger en masse than the localized tests indicate.

PERMEABILITY

Water may move through the intergranular pore spaces in sedimentary rocks as well as through channels along bedding planes, fractures, joints, faults, and solution channels. Two general foundation problems arise from permeability of the rock: uplift and leakage. Uplift is the buoyant effect of water on a submerged foundation. Leakage is the passage of water through a foundation and is of primary importance in the determination of the economic feasibility of a project.

Uplift has been the subject of considerable thought and discussion recently, much of which has been summarized by Harza (1947) and others with the result that it is commonly assumed in the design of a structure with a submerged foundation that the entire base of the structure is subject to uplift pressure, regardless of the type of rock upon which it is founded. There remain then to be determined the intensity of the uplift at any point in the foundation and a means of reduction of that pressure. The pressures may be closely determined by the construction of a flow net. Construction of a grout curtain will reduce the leakage but not the uplift pressure. The reduction of the uplift pressure can be effectuated only by provision of relief. This is usually in the form of nearly vertical drainage wells or drain holes drilled in the foundation rock downstream from the grout curtain, as close to the zone of maximum pressure as feasible and connected to a collector system in the basal portion of the dam. The direction of these holes, their size, spacing, and depth should be dependent upon the type and structure of the foundation rock and its post-construction characteristics, because the methods of construction and type and extent of foundation treatment may modify or obliterate the necessity for draining certain elements of the foundation rock.

Leakage beneath structures has been encountered in varying degrees in projects located on all types of sedimentary rocks. Leakage can be reduced to a negligible minimum by finding and cutting off stratification, fracture, and solution channels that would allow water to by-pass the structure. The prime purpose of leakage reduction is to prevent the escape of water for whose storage the structure was built and upon which storage the economics of the project depend. The safety of the structure should not be endangered by the free passage of water through its foundation. Although limestone is only slowly soluble, it, like any other rock, is subject to mechanical erosion. Theoretically, then, it might be permissible to reduce leakage in a limestone foundation to a point where velocities of flow are mechanically non-erosive, if the economics of the project were not materially affected. Such could not be permitted in a foundation containing gypsum or salt. As a matter of good practice the intent of all grouting and waterproofing treatment of foundations is to reduce leakage to the absolute minimum feasible under the circumstances. The problems involved in controlling leakage require the determination of the location, extent, and size and interconnection of actual and potential channels of leakage, and the means of cleaning and closing off or filling these channels. The solution of these problems requires the application of many geologic techniques including detailed investigation of the sedimentary features of the rock (Moneymaker, 1941).

CLASSIFICATION OF SEDIMENTARY ROCKS

The sedimentary rocks may be separated into innumerable types, depending upon their chemical composition, geologic history, mode of deposition, grain size, primary structure, texture, and mineralogical composition. However, in relationship to foundations they may be grouped into two broad classes: soluble rocks and insoluble rocks. The insoluble rocks include rocks composed of essentially insoluble minerals bonded with generally insoluble cement in which naturally cavernous conditions do not occur. Examples of this type of rock are sandstone, siltstones, shales, indurated clays, mudstones, claystones, coal and other carbonaceous rocks. Soluble rocks include limestones, dolomites, and evaporites in which cavernous conditions have occurred or may occur. Soluble and insoluble rocks may be closely associated as in an interbedded sequence. The determination of appropriate classification depends on the extent of past or potential solution and its influence on the type of foundation problem. The typical association of insoluble and soluble rocks is the interbedding of shales and limestones. Another condition, less recognized from the standpoint of foundations, is the cyclic deposition found in the Carboniferous rocks of the Appalachian and Interior coal basins of the United States where nonmarine and marine sediments contain limestones as well as insoluble members.

INSOLUBLE ROCKS

Insoluble rocks can be separated into rock types based primarily on their grain size, mineralogical composition, cement, and frequency of bedding. The foundation problems of these rocks depend almost entirely on the physical properties of the rock which are closely related to the foregoing geologic characteristics. Except for the siltstones of the

Appalachian Basin the physical strength and intergranular permeability decreases, in general, with decrease in grain size and increase in clay content.

Coarse-Grained, Insoluble Sedimentary Rocks

These rocks include the sandstones, conglomerates, and sedimentary breccias. Commonly these rocks have been well cemented. The bedding varies from an inch or two in thickness up to over 20 feet. Cross lamination is common. The rocks may be considered competent rocks which have reacted to deformation with the development of joint systems and fractures and, in the case of faulting, have produced breccia and gouge zones containing granular material. Structurally the coarse-grained insoluble sediments may be characterized by three sets of planes referable to bedding, cross lamination, and deformational jointing. On these may be superimposed faulting. From the standpoint of physical characteristics, these rocks are among the hardest and most durable materials upon which a structure may be founded. With the cementation of the rock by silica the sandstones assume the physical characteristics of a quartzite, and compressive strengths as high as 34,960 pounds per square inch have been recorded (Eckel *et al.*, 1940). On the other hand, compressive strengths as low as 120 pounds per square inch have been found in the poorly cemented sandstones. In general, compressive strengths are of the order of 10,000 pounds per square inch, and shearing strengths, in pounds per square inch, of $770 + 2.60p$, where p equals intensity of load on the plane of shear, are found. With these physical characteristics, the average sandstones, sedimentary breccias, and conglomerates are commonly acceptable foundation materials when considered within the bounding planes of the test specimen. The chief difficulty with the sandstones lies in their brittle character, which has caused them to fail under deformational forces and produce not infrequent cracks and occasional zones of pervious granular material along faulting planes and occasionally along the major system of joints. Because of the high intergranular permeability of some sandstones, uplift pressures may approach the theoretical maximum.

Mahoning Dam on Mahoning Creek, Armstrong County, Pennsylvania, is a gravity dam about 176 feet high above the stream bed founded on a sandstone which, in laboratory tests, indicated strengths many times those required to support the load of the dam. The usual small- and large-diameter core borings indicated no structural flaws in the foundation and showed a low anticlinal nose plunging down the dip of the regional structure. However, when the foundation was exposed, a branching thrust fault carrying about 18 inches of gouge was encountered just below the foundation level at one side of the spillway and some 20 feet deeper on the other side. The fault required the excavation of the overlying material to a depth of about 20 feet, where the gouge thinned and became sufficiently granular to permit consolidation by shallow pattern grouting.

The sandstone foundations are commonly acceptable, subject to geologic structural weaknesses not reflected by laboratory tests and related to the inherent characteristics of the rock en masse.

Medium-Grained, Bedded, Insoluble Sedimentary Rocks

These rocks include siltstones and some of the coarser shales. The general characteristics of the siltstones are similar to those of the sandstones with the exception of permeability, which is commonly lower in the siltstones. Physical tests of siltstones in the Appalachian Basin indicate compressive strengths of 8,800 pounds per square inch and shearing strengths, in pounds per square inch of $800 + 2.4p$. The reaction of siltstones to deformation is similar to that of sandstones. In general, then, siltstones are similar to sandstones as foundation materials, although somewhat weaker.

Fine-Grained, Laminated, Insoluble Sedimentary Rocks

These rocks are the common shales, they vary greatly in character, and they constitute some of the most difficult foundation rocks. The shales are distinctively thin-bedded to laminar and composed of laminar minerals which lie parallel to the bedding. Shales are characterized by an established plane of potential weakness on which may be superimposed regional and local systems of joints, fractures, folds, and faults. The bedding may be disturbed by prelithification distortion, as in some of the near-shore deposits, or it may remain almost planar in its smoothness.

The minerals are usually micas and clay minerals with varying amounts of silica. The intergranular cement may be siliceous, calcareous, or, less frequently, ferruginous, or intergranular cement may be lacking entirely. The first type of shale has been termed by Mead (1938) a "cemented" shale, and the second type a "compaction" shale. The physical properties of these two pure types differ considerably. The difficulty of the foundation problems seems to increase with the decrease in cement and resulting decrease in strength and durability. The cemented shales behave more like rocks and are variably elastic, whereas the compaction shales behave more like soils in relation to stress. There is no hard and fast line separating these two types of shale, nor is one possible inasmuch as most shales are partially cemented and partially compacted rocks. The simple weathering test, which is the behavior of the rock during five successive cycles of wetting and drying with water or 100 N ammonium oxalate, seems to be the most revealing of the coherent quality of the shale. Those shales which are reduced by this process to uncohering aggregates of approximately grain-sized particles are compaction shales. Those which are entirely unaffected or reduced only to flakes are cemented shales. This test also indicates the behavior of the shale upon exposure to atmospheric conditions during construction.

The chief problem with a shale is the determination of the physical characteristics of the rock from the standpoint of design criteria. Such a shale has been described by Rountree (1940, p. 1539) as follows:

> The shale underlying the easterly portion of the Watts Bar Dam is a part of the Rome formation and is classified as a cemented, clay and silty shale. It is fairly compact and, in general, unweathered. The shale is characterized as "fissile" and is comprised of very thin layers which are easily separated; the surfaces of these layers are smooth and glossy in appearance. The shale is interbedded with thin layers of hard sandstone which vary from ⅛ inch to 2 inches in thickness and which are normally from 1 inch to 24 inches apart. In general the shale has a dip angle of from 20° to 30°, but occasionally, in limited areas, the bedding planes are horizonal. The apparent weakness of the material against movement parallel to the bedding prompted these tests.

The field load tests were conducted on six blocks of concrete poured on the shale which had been trenched to a depth of 2 inches around the base of the blocks. The shearing strength of the shale was appraised at a value in tons per square foot intermediate between $0.9 + 0.43q$ and $0.8 + 0.35q$, where q is the intensity of load on the plane of shear. The value of the coefficient of friction of shale sliding on shale, parallel to the bedding planes, was determined as something less than 0.53 (Rountree, 1940, pp. 1542–1543).

If it is assumed, then, that in a shale foundation the physical properties of the shale are known, what effect do its geological properties have upon the design of the foundation? If the materials are homogeneous and infinite in extent, the geological properties are defined by the physical properties. But in practically all cases the shale is not homogeneous and infinite in extent. Therefore one is forced to consider the inherent geological properties. The most important are: the interbedding of softer, thin layers; dip; fracture systems; and durability upon exposure. Usually these can be defined only by visual investigation of the rock in place through preconstruction shafts and tunnels, although their presence may be indicated by surface exposures. Not infrequently shales carry variably open bedding planes along which there may be very soft veneers of clay. With these conditions it is almost impossible to define physical properties exactly, and large safety factors are considered in the calculations of stability and built into the structure. As an example, the base of the foundation may be inclined so that the angle of the resultant of all forces tends to be more normal to the foundation surface, with the result that the foundation rock is engaged to a greater depth, thus reducing the influence of weaker zones immediately below a level, higher foundation surface. Similar results are obtained by the construction of shear walls suitably anchored to the structure and extending below the base of the remainder of the foundation of the structure. But in general the tendency in overcoming geological weaknesses in shale foundations is to reduce the unit loading by broadening the base of the structure or reducing its weight and founding it well below the surface of sound bedrock. The concrete of the foundation is placed directly against the rock enclosing the excavation. Advantage is taken, thus, of the shearing resistance of the rock mass into which the foundation is keyed.

The foundation problems of the "immature" shales of the Fort Union formation represent the other end of the transition between the foundation problems which are controlled by the geological characteristics of shales and those which are controlled by the physical characteristics of shales. Golder, in a personal communication dated February 9, 1949, has described these materials at the site of Garrison Dam, North Dakota, as follows:

> The Fort Union is composed of nearly flat-lying fine sands, silts, and clays (with clayey phases predominant), limestone and lignitic horizons of Paleocene age, ranging from thin partings to beds over 15 feet thick. These sediments have been described both as clays and shales, but we feel that they are something in between these two, and should be called immature shale. There is little cementing material in the Fort Union and most of the standard soils laboratory testing procedures are applicable to the sediments of this formation.

Shear tests of undisturbed samples show that the cohesive strengths range from practically 0 to almost 2 tons per square foot with angles of internal friction ranging from 15° to 34°. The foundation problems arising from the necessity to construct massive structures on these sediments include the determination of the safe bearing values by test procedures and the preservation of the rock during construction and prior to the placement of concrete.

Fine-Grained, Insoluble Massive Sediments

These rocks are fine-grained argillaceous sediments comparable in almost all characteristics to the shales with the exception that the bedding is infrequent. They seem to occur sporadically through the geologic column from the Paleozoic into the Tertiary. They are variably cemented and, like the true shales, exhibit decrease in strength generally with a decrease in intergranular cement. Field tests of such materials, made in connection with Possum Kingdom Dam on the Brazos River, Texas, to obtain the limiting data upon which to base the criteria of design of a safe structure, are summarized by Niederhoff (1940). The Bear Paw shale at the site of Fort Peck Dam, Montana, is another of the massive argillaceous sediments which has been extensively investigated. However, at Fort Peck the foundation problem was complicated by the presence of bentonitic beds, variable weathering, and considerable faulting. The problems there involved the testing of foundation rock in the laboratory by means of undisturbed cores, the preservation of the rapidly disintegrating rock during construction, and determination of permeability of bentonitic seams. As most of these massive argillaceous rocks are poorly cemented and owe their strength to compaction produced primarily by the weight of the overlying sediments, it is not unusual to find that such rocks expand with reduction in load resulting from removal of the overlying rocks. At Fort Peck the Bear Paw shale has expanded in the spillway area and heaved the spillway pavement.

Foundation problems in these rocks are subject to closer determination by methods of direct testing than problems in the other argillaceous rocks as these rocks tend more toward homogeneity.

Cyclic Sediments

The concept of cyclic sediments has been applied only recently to foundation problems (Philbrick, 1947), although structures have been built on cyclic sediments for many years in the Carboniferous of the Appalachian and Mid-continental coal basins of the United States. Practically all the problems of both shale and sandstone foundations, together with those of coal and limestone foundations, occur in a single sequence in a cycle, and several cycles may be present at a site. For a low structure the problems are usually those of the rock type which happens to be the bearing bed. In a structure higher than the thickness of the strata composing the sedimentary cycle, the problems of the several rock types present in the cycle will be repeated. Difficulties encountered in the design and construction of Tygart Dam and Lake

Lynn Dam in West Virginia (Crosby, 1941) were primarily the result of cyclic sedimentation.

A cycle in the Coal Measures usually, but not always, is composed of the following rocks, from the base upward: sandstone, shale, fresh-water limestone, under clay, coal, shale, marine limestone, and shale. Dissimilarity of physical properties of contiguous rocks is the dominant characteristic of the cycle from the standpoint of foundations. The sandstones may be hard massive rock. The shales and under clay may be soft to medium hard and fissile to massive. The limestones range from pure limestones to nodular limy shales or clays. The coal is brittle. To even minor geologic deformation the several rock types react differently. The sandstones, sandy shales, and carbonaceous shales behave as competent beds and fracture. The weaker members fail by plastic flow with the development of numerous, random, slickensided surfaces. The coal develops a blocky structure, and the limestones usually develop a fracture system. None of these systems necessarily parallels the system of a contiguous member. The rate and degree of weathering vary with each rock type. Localized zones of weathering are found at the base of the pervious members. Inherently soft materials are found at the top of the impervious members underlying pervious members. The result is that, from the standpoint of design, the foundation is heterogeneous. Sampling of each bed or type of bed is required to produce data upon which to base the design of that portion of the structure controlled by the characteristics of that bed. The individual portions of the structure may require individual design. During construction, certain rocks must be protected from weathering and disintegration, whereas other members can be left completely unprotected. The plan of excavation is dependent upon the extent of weathering in the several rock types and the quantity of material that may be removed without permitting deleterious expansion of the underlying compaction shale members. Bond between concrete and foundation rock may be virtually unobtainable in some of the compaction shales and the under clay without very careful preparation and cleaning. It is usually safer to place foundations only on the cemented shales and sandstone. This causes the foundation to be cut on nearly vertical slopes at monolith joints and requires the exercise of great care in excavation and protection of these riser faces.

The cyclic sediments require as much care in foundation investigation, sampling, testing, design, treatment, and construction as any of the sediments, because almost all the problems of the other sediments are found in the cyclic sediments. Although the problem of extensive natural leakage is not commonly met, artificial leakage channels may be present in the form of coal, clay, or limestone mines. In the case of structures requiring support only, it is not uncommon now to find the site of the structure underlain by a coal mine which may have been abandoned for many years or on which few or no data are available. Such a mine may be accessible only under dangerous and adverse conditions and not infrequently only through new shafts or entries. Such mines may be grouted (Philbrick, 1948) or backfilled with stable, free-draining materials as is common at present in the anthracite fields of Pennsylvania. If sufficient data are available on the extent of mining, the distribution of pillars, and the character and thickness of overlying materials, it may be feasible to disregard the mine entirely. If the mine is on fire, it is wise to find another site rather than attempt to put out the fire and utilize that site.

Soluble Sedimentary Rocks

Much has been written on the foundation problems of soluble sedimentary rocks, and feasible solutions to the problems of leakage control have been developed (Lewis *et al.*, 1941). Although tests of unconfined 6-inch cores of the Ocala limestone have indicated compressive strengths of as low as 64 pounds per square inch, in general the common limestones and dolomites are ample in supporting capacities both in shear and in compression for a dam less than 300 feet in height. The nature of the rock and the usual rough surface developed during construction reduce to an academic consideration the problems of failure by sliding. However, limestones may carry, close beneath the base of the proposed structure, thin partings of shale which require consideration of their properties in the design of the structure or excavation to below the shale. Certain limestones carry bentonite beds which require similar investigation and treatment. It is generally assumed that the rate of solution of limestone and dolomite is sufficiently slow to have no bearing upon the safety of the structure.

Chalk, such as the Niobrara in Nebraska (Happ, 1948) poses a different problem. Happ has described the fresh Niobrara as a fairly dark gray, fine-grained, compact, brittle, soft chalky limestone cut by thin horizontal layers of bentonitic clay ranging from a small fraction of an inch to 4 inches in thickness, the majority being very thin. It has an average dry weight of about 100 pounds per cubic foot and a compressive strength ranging from about 250 to 2,400 pounds per square inch and averaging about 1,000 pounds per square inch. The bentonitic clay layers in laboratory shear tests showed values in cohesion ranging from 0.1 to 0.4 ton per square foot with tan ϕ ranging from 0.06 to 0.23. In this case the problem is not that of providing effective cutoff of pre-existing water channels as in limestone terranes, but rather of designing a structure on soft rock cut by seams of softer rock, the latter being subject to disintegration upon exposure and to expansion upon release of load with the removal of overlying materials.

Some structures have been built on gypsum and on salt, and others are being considered for sites containing these rapidly soluble sediments. The problems concern the geologic dating of collapse of caverns leached in the gypsum, the determination of the present water table, and the effect of the increased height of the water table on the rate of solution of the soluble sediments. Where it has been proved that the gypsum is effectively cut off by impermeable beds from the additional hydrostatic head, reservoirs have been successfully constructed and operated over gypsum. For salt the situation is similar. The general rule in considering foundations containing rapidly soluble sediments is that another site is probably better. However, if no other site is available, the site should be considered as one on which a flexible structure capable of withstanding some settlement should be designed because there are as yet available insufficient data to warrant an assumption of the rate of solution of these sediments. The laboratory rate of solution of gypsum in a bath may be highly misleading, or it may be approximately the rate of solution *in situ*.

CONCLUSION

In many cases it may be more economical and equally desirable to design for the worst rocks in the foundation, even though this may mean an apparently more expensive structure, than to attempt to raise the values of these rocks or to remove them and found on stronger materials or choose another site where better rock may be present closer to the ground surface. It should be recognized that foundation treatment (the all-inclusive term applied to "monkeying" with a foundation) can be most astonishingly expensive even when compared with the cost of a major project. On the other hand, it may be considerably cheaper to invest a large sum in improving foundation conditions at a site than to reduce the magnitude of the structure and build other smaller supplementary structures, particularly in the case of a coordinated river development scheme or in the case of a high bridge. The economic treatment of foundation problems is intimately related to the general engineering and economic features of the entire project, and they may dictate the general permissible scope of the foundation treatment.

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CHAPTER 9

FOUNDATIONS FOR HIGHWAY BRIDGES AND SEPARATION STRUCTURES ON UNCONSOLIDATED SEDIMENT

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Bridges, in common with all other civil engineering works, must be dependent for support upon earth materials. Since bedrock support is the exception rather than the rule, it is appropriate that space be allocated in this volume to a brief discussion of foundation study tools and techniques applicable to the solution of problems involved in the frequent practice of transmitting structure loads to unconsolidated sediment.

The engineer is often confronted with serious problems posed by the design and construction requirements of safe economical support for bridges. This is particularly true when a dependence for support must be placed upon recently deposited sediment which has not been subjected to loads greater than those which exist at present.

The purpose of this chapter is to present a description of some of the tools, methods, and personnel requirements of a modern foundation investigation. It is hoped that by so doing additional interest may be encouraged among workers engaged in this and related fields of applied sedimentation, to the end that reflections may be observed in both the curricula of personnel training and ultimate practical achievement in this important field of application.

Normally the bridge engineer is allowed little choice regarding the location of his structure because such determinations are usually dependent upon the requirements imposed by highway grades and alignments. This situation presents the problem of economic conformity to any type or variety of material types that occur at a specific site regardless of either the physical characteristics of the material or the magnitude of the problems involved. It follows that, if economically sound, practical substructure designs are to be consistently realized, they must be based upon accurate observations and interpretations of the natural foundation conditions at each structure site. Obviously this goal can be accomplished only through the development and use of trained personnel and special-purpose tools.

The list of references at the end of the chapter has been carefully selected for the benefit of those who may desire reference to technical discussions of the various aspects of foundation investigation and interpretation practices.

PERSONNEL REQUIREMENTS

Men charged with the conduct and interpretation of foundation investigations for highway structures hold responsible positions. It is extremely important that an accurate picture of existing conditions be obtained for design purposes, and it is equally important that construction operations actually encounter predicted conditions in order that costly delays in construction, redesign requirements, contract change orders, legal suits, and, in extreme cases, structural failures may be avoided.

The choice of the foundation type alone may seriously influence the economics of a project. For example, a careful estimate revealed that, for some seventeen of the many separation structures to be constructed on one of the freeways through the City of Los Angeles, the State of California would realize a saving in excess of one million dollars in the event that the sediment was capable of supporting the loads on footing foundations and pile supports could be eliminated. Determinations of this sort require precise measurements and careful consideration by well-trained and experienced personnel if the bridge engineer is to have sufficient confidence in the recommendations he receives to design and construct accordingly.

It is anticipated that many universities and colleges will follow the recent example of the few that have inaugurated curricula in engineering geology for the purpose of training interested students for this important field of geologic application. It is hoped that the term engineering geology will be interpreted in its proper light and that steps will be taken to insure that students who enter this field through interest and choice will be encouraged to obtain an educational background in civil engineering as well as geology.

The "make it stout" complex so prevalent among substructure designers today is the natural outgrowth of works without faith. We can have little faith without understanding and little understanding without knowledge born of interest. Consequently foundation studies should be conducted by men whose prime professional purpose in life lies in the scientific study and interpretation of nature as applied to civil engineering. It is not important whether these men call themselves engineers or geologists. The real requirement is that they be both.

FOUNDATION STUDY TOOLS

The foundation study for any highway structure should consist fundamentally in determining the proper methods of applying loads to earth materials in amounts that will not result in excessive settlement or failure. If the structure is to span a stream, additional consideration must be given to insure against structural failure due to scour in the channel or erosion of the banks.

It is of prime importance that field parties charged with the determination of foundation requirements be equipped with the modern tools of their trade.

Hole-boring tools capable of penetrating and sampling all types of earth material to any required depth are an essential part of foundation study equipment. In most cases it is desirable that boring tools be power-operated and at the same time sufficiently light and portable as to insure access to sites located in areas of troublesome relief. The boring equipment should be capable of drilling rotary wash boreholes up to 3 inches in diameter and to depths of about 200 feet. Contrary to the general opinion among engineers, wash boring is by no means a worthless technique in so far as its applications to foundation studies are concerned. It is the writer's experienced opinion that borings of this type furnish valuable information at the lowest possible cost per lineal foot when properly conducted under the close observation of adequately trained personnel. This technique, when used in conjunction with spot sampling of the significant horizons, may in some cases fulfill all the requirements of an adequate study. This is particularly true in areas where the geology is well understood or where an experience has been gained by observing the performance of existing structures within a geologic provenance. The drilling machine should in addition be equipped with bits, core barrels, and samplers capable of the efficient penetration and sampling of earth materials regardless of type or depth.

A small drop hammer or other suitable device is required for the purpose of driving casing, penetrometers, and sediment samplers. Although light drop hammers are in general use for this purpose, it has been demonstrated that small-diameter undisturbed samples show less disturbance when samplers are forced into the sediment by means of a steadily applied hydraulic or screw-activated push or by a rapid, explosive percussion blow (Creager, Justin, and Hinds, 1945, p. 19). The resistance the sediment offers to tool penetration and extraction is commonly an important measurement of sediment character. This is particularly true when procedures are standardized and measurements are recorded by properly calibrated gages as attested to by results of the standard penetration test (Terzaghi and Peck, 1948, p. 265).

Undisturbed sediment or soil samplers capable of delivering samples in a reasonably undisturbed state are essential if some of the more significant soil mechanics tests are to be conducted. Of the many types of samplers on the market, the thin-walled types, in general, meet most of the sampling requirements. Certain situations, however, such as the procurement of samples of very soft mud, clean uniform saturated sand, or the sampling of sediment at the proposed tip elevation for bearing piles, may require the use of special-purpose sampling spoons. It should be kept in mind at all times that no amount of undisturbed sampling or testing is of any great significance if the sampling procedure does not, or cannot on an economic basis, result in the procurement of representative samples of the sediment in a sufficiently undisturbed condition to permit accurate evaluation of the control criteria by means of standard testing procedures. It is the engineering geologist's job to determine whether or not the samples are representative of the true conditions. If the site is one of such complexity that samples are not diagnostic, the recognition of this fact is extremely important, and the problem may then be handled by means of an adjustment in the safety factor or by incorporating extra flexibility in the contract specifications.

The large array of boring-tool types, samplers, penetrometers, and other special tools designed for the foundation study purpose furnishes ample evidence of the fact that there is no universal tool panacea for work of this nature. Among the control factors regarding the choice and extent of tools are the amount of foundation investigation work to be done by any specific agency, the degree of geologic complexity or variability of the general area and specific site of operation, and the size of the project. Many thousands of dollars have been wasted for the want of proper equipment to conduct efficient foundation studies. Numerous attempts have been made to solve the problems presented by complex or erratic conditions of sedimentation by literally drilling the site full of holes, taking continuous undisturbed samples, and conducting innumerable shear, unconfined compression, consistency limits, moisture, density, permeability, consolidation, etc., tests, when possibly all that was required to be determined was how far steel piles would penetrate, or perhaps the feasibility of supporting the load by means of friction piles. These answers might well have been obtained by driving penetrometers at a few selected locations throughout the structure site; the resistance offered to penetration could have been observed, and, after appropriately spaced time intervals, periodic pull tests designed to measure skin friction values could have been conducted. Test pits in large numbers and to great depths have been dug after the inability to penetrate a deposit of loose boulders and gravel to bedrock depth by means of available drilling equipment has been established. This discovery is usually made after at least one of every type of drill bit available has been destroyed in the attempt. Refraction seismic equipment or certain electrical geophysical apparatus could have revealed the answer for a mere fraction of the expended time, energy, and money. Although current researches have not resulted in the ultimate with regard to applying geophysical techniques to mantle exploration, much progress has been made in recent years, and the future looks very hopeful (conference with Dr. Thomas Poulter, January 1949).

In addition to equipment capable of solving the drilling, penetrating, and sampling requirements of a foundation study program, it is equally important that the field party conducting such studies have available sufficient testing apparatus to permit on-the-job measurements of important physical characteristics of the sediment.

Pumping tests should be conducted in drill holes or wells in cases where footing foundations are to be situated below the water table or where high permeability is likely to exert a major influence on the builders' operation. Quick shear or unconfined compression tests or both, when conducted in the field, often give results that may influence or control the conduct of the entire study program. Percent voids, unit weight, moisture content, the consistency limits, and grain-size classification can, and should, be determined in the field. This procedure not only develops better-trained personnel but also places sampling and testing directly on a job-requirement basis. It is not suggested that all laboratory-type testing be done in the field. Triaxial shear, time consolidation, petrographic analysis, and most chemical tests require permanent laboratory facilities and can be properly conducted in no other place.

Since the advantages offered in the form of checks on both dynamic measurements and the judgment of the engineering geologist far outweigh those of permanent laboratory facilities for certain measurements, field testing is strongly recommended whenever feasible.

EXPLORATION PROCEDURE

The first step in the conduct of a foundation study for a highway structure should consist of a complete determination and understanding of the general geology of the area. The foundation condition at each structure site, whether complex or simple, is the direct result of the geologic processes, environment, and history of the area. If an understanding of these factors is not acquired first, the study becomes a routine matter of boring holes in the ground and conducting monotonous tests rather than an interesting interpretation of the complexities of nature. The second step consists in ascertaining the physical character of the sediment for the purpose of determining specific foundation requirements at the sites of structure support.

The depth to which borings or soundings should extend, and the spacing between borings, should be dependent entirely upon the complexity of the site, the size of the project, and the depth to compressible sediment occurring within the limit of surface-load influence. Any attempt to standardize boring depths or distances between borings is obviously dangerous and to be avoided. Each structure site requires its own individual explorational treatment, and any attempt to predetermine the study requirements or procedures usually leads to inefficient operations and faulty results. There is no substitute for adequate training and experience when the proper study procedure for a foundation problem, or the accurate determination of the time when further study will cost more than it is worth, is being selected.

FOOTING FOUNDATIONS

In those cases in which scour or lateral erosion is not indicated and in which the boring logs and sounding patterns or both do not reveal the existence of soft compressible sediment within the significant depth of surface-load influence, the structure may be supported by footing foundations resting upon near-surface sediment (Taylor, 1948, p. 560; Terzaghi and Peck, 1948, p. 56). All footings must be located below the influence of frost and seasonal moisture.

No precise statement can be made with regard to the depth to which footing foundations may extend and render structural support in economic preference to pile foundations, because this determination must be made for each substructure in the light of allowable bearing value of the sediment, depth of seasonal volume change due to moisture, frost, plants, etc., depth of scour, span lengths; live, wind, earthquake, and dead loads; and allowable settlement. This is, however, an important phase of the economic study of the substructure and one that requires careful consideration.

Every foundation should be designed for a factor of safety comparable to that used in the design of superstructures. This factor should be applied against the possibility of the foundation failing as a result of applied loads exceeding the shear strength of the supporting sediment, sliding upon the contact between the footing block and the supporting earth material, sliding upon bedding planes of the sediment, or excessive settlement due to compressive materials. This factor of safety should not be less than $2\frac{1}{2}$, and it rarely needs to exceed 3. It is not uncommon in present practice for factors of substructure safety to be as high as 20. Such a design policy rarely results in a foundation failure in the normal sense, but it does cost untold thousands and thereby represents economic waste.

The total settlement of the structure should not exceed that which may result in differential settlements in amounts capable of either damaging the structure or developing a poor riding deck. Differential settlement between adjacent supports will usually not exceed 50 percent of the total settlement unless the loads are vastly different or the foundations are of different types; for instance, adjacent bridge piers supported by pile and footing foundations respectively. In such cases the differential settlement may approach 100 percent of the total settlement.

Precise settlement computations are rarely justifiable for highway structures except when firm support cannot be reached by piles, columns, or caissons because of great depth, or when soft compressible sediment occurs beneath the footing at a depth sufficiently shallow to permit consolidation under the applied load (Terzaghi and Peck, 1948, pp. 413–456; Plummer and Dore, 1940, p. 192).

Considerable money could be saved by a more extensive use of the flexible-hinge design for structures where serious differential settlements are anticipated. Hinge design, together with facilities for jacking, would, for example, make it possible on many occasions to use floating abutments on fills through which piles are commonly driven.

Load tests on bearing plates, when accompanied by data that identify the character of the sediment within the significant depth, furnish valuable information regarding the load-carrying ability of the supporting material. Such tests, although generally considered expensive, can, with properly designed equipment, be conducted on a routine basis at low cost. Load tests at the sites of pier locations for the Plaza Garage Overhead structure on U. S. 99 north of Visalia, California, proved conclusively that footing foundations will safely support loads of 3 tons per square foot at a depth of 7 feet. The cost of the tests was only a small fraction of the saving realized as a result of pile elimination. The load tests in this case were conducted in large-diameter holes drilled with a power-driven bucket auger on plates having a surface area of 2 square feet. The load was applied by means of a power-operated hydraulic pressure cell. Constant pressure was maintained by use of a nitrogen-loaded gas accumulator and a mercury pressure switch. Twelve-inch expanding anchors fixed in drill holes furnished adequate load reaction.

Load tests on bearing plates must be used with a full appreciation of the limitations of the method. It should be kept in mind that the test reflects only the character of the sediment to a depth of about twice the diameter of the bearing plate, whereas the footing foundation will exert an influence on the underlying sediment to a depth at least as great as the footing width for ideal conditions, and to a depth several times the footing width if the sediment becomes softer and weaker at depth.

The depth below the footing elevation to the water table is of considerable importance, particularly in the case of footing foundations supported upon cohesionless sediment. If the water table rises within the significant depth, the factor of safety should be increased from 2.5 to 4.

Large footings settle more than small ones if unit loads are the same. For example, allowable loads should be reduced from 6 tons to approximately 5 tons per square foot on dense sand where the footing width is increased from 5 to 10 feet. It is not advisable to attempt to support footing foundations for highway structures on soft clay or plastic silt except as a last resort. Differential settlements up to 6 inches are commonly unavoidable in such cases, and total settlements amounting to nearly a foot have been measured.

It is not advisable to apply loads to footing foundations supported by plastic sediment in amounts that exceed the unconfined compressive strength of the weakest material encountered. If weak plastic sediment occurs at some depth below a firm stratum upon which footings are to rest, a calculation is required for the purpose of determining the load distribution at depth and, thereby, the amount of load that will be applied to the weak sediment. A safety factor of 3 should then be used against overstressing the weak stratum.

PILE FOUNDATIONS

Pile support for highway structures should be used only in those cases in which footing foundations cost more or are unsafe because of the possibility of erosion, or where settlements are apt to be excessive.

The engineer has, through experience, acquired a deep respect for the complexity and variable nature of foundation conditions. As a result, pile foundations occupy a hallowed niche in the engineering profession and are apt to be used, not necessarily when needed, but whenever possible. The limits of possibility, when confronted with engineering ingenuity, have, needless to say, been pushed back quite a way.

Piles may be classified on the basis of load-transfer method into two general types:

(1) Friction piles. Those which transfer the imposed structure load to the surrounding sediment largely through skin friction.

(2) Bearing piles. Those which transfer loads to a firm or hard material at depth largely through the pile point contact.

It should be noted that friction piles support a portion of the load in the manner of bearing piles and that bearing piles transfer a portion of their load to the sediment through skin friction. Therefore, in order to estimate the load-carrying capacity of a single pile, both friction and point-bearing data must be obtained in most cases.

Carefully conducted wash borings, together with a few spot samples, usually suffice for sediment classification purposes. Drive or push soundings when accompanied by penetration tests will yield valuable data regarding pile length requirements and point bearing values. Pull tests spaced at proper intervals of time and conducted at significant depths, and locations throughout the structure site as previously determined by borings, will permit reasonably accurate estimates of skin-friction values. Friction values determined by the pull-test method in plastic sediment may be checked by means of direct shear or unconfined compression tests, and those in granular sediment by the standard penetration or triaxial shear tests or both. A few test piles and full-scale load tests should be insisted upon in all cases in which structural support is to be derived from friction piles.

The use of pile-driving formulas for measuring the ultimate bearing capacity for individual piles should be avoided in all cases in which resistance to pile penetration is due to friction between the pile and cohesive silts or argillaceous sediment. Allowable loads in such cases should be determined by use of a safety factor of not less than 2 when used in conjunction with load tests approved by the American Association of State Highway Officials, Standard Specifications for Bridges (1949).

Settlement determinations must be made in all cases in which soft plastic sediment occurs within the significant depth below the pile tips, or in which the load-carrying capacity of the pile group or cluster is less than the bearing value of the cumulative capacities of the piles within a cluster (Seiler and Keeney, 1944; Moore, 1947, pp. 1341–1358).

CONCLUSIONS

There is a growing insistence among bridge engineers that precise foundation data are a prerequisite to efficient substructure design. This insistence is commendable and completely justifiable within the limits of our present understanding of nature, and it is plainly up to us as engineers and earth scientists to accept the responsibility for our present state of knowledge, foster the extension of our knowledge and understanding at every opportunity, and encourage the prompt application of practical truths to the design and construction of current projects.

The foundation specialist must have a keen sense of the economics involved in his work and must not become so carried away with his study program that he loses sight of his justification in a conscientious attempt to know all the answers prior to construction. A foundation study is not over when the borings are completed and the testing done; it should be continued through observation and study during the period of construction and ultimate use. It is only by so doing that we learn of our mistakes and are able to accumulate a stockpile of corrected data for our future use or the use of those who follow.

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Chapter 10

EARTH DAMS

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The major civil works activity of the Corps of Engineers is the construction and maintenance of dams and levees for flood control and navigation purposes. More than one half of the dams and all the levees are earth structures founded on a variety of geologic formations varying from sound rock to overburden soils. An application of soil mechanics principles to the design of these earth structures has resulted in safe and economical construction. However, soil mechanics is by no means an exact science and is dependent in a large measure on a proper understanding of geologic formations to interpret the results of foundation explorations. In the writer's opinion, close cooperation between soils engineers and engineering geologists is essential in the design and construction of earth dams and levees. Investigational, design, and construction features of earth dams are covered in this chapter with specific reference to soil mechanics and geological aspects of all phases of the work. Details of exploration and design have been purposely omitted because they are adequately covered in other publications.

GENERAL FEATURES

The selection of a dam site involves many factors, among which the geologic and soil mechanics features are of prime importance. Usually a site study must be confined to a limited reach of river channel in order that the dam may perform its required function. Unless conditions are obviously favorable at a particular location, regional geology should be studied. During the preliminary studies the site having the most favorable topographic features for the location of the dam and the spillway is selected for more detailed study. The detailed site study should develop the nature of the overburden and rock foundation in the river valley and abutments. Special attention should be given to foundation conditions at all possible spillway locations in order that the most economical spillway that will perform the specified functions may be designed. Foundations for outlet works should be thoroughly explored to determine whether a "cut and cover" type of conduit or a tunnel is preferable.

Selection of the type of dam, whether concrete, rock-fill, or earth, has been adequately covered in other publications (Creager, Justin, and Hinds, 1945; Middlebrooks and Bertram, 1948).

FOUNDATION STUDIES

A study of foundation features of an earth-dam site may be divided into three general classifications: (1) investigation of foundations for the spillway structure; (2) investigations of foundation for the earth dam; and (3) investigations of foundations for the outlet structure. After the general geological and soil study of the site, a detailed study should be made for each of the three structures enumerated.

SPILLWAY STRUCTURE

In order that sufficient geological information may be furnished the designers, the geologist and the soils engineer should have a general knowledge of different types of spillways and the foundation requirements for each. In Figs. 1 through 6 are shown a few examples of various types of spillways and typical foundations upon which they are used. The spillway type should be varied to fit not only the foundation but also the frequency of use of the spillway. At most earth-dam sites the spillway design presents a major problem and represents a high percentage of the total cost of the project. Therefore a careful foundation study of all possible spillway locations should be made.

A gravity overflow spillway as shown by Figs. 1 and 2 presents fewer operational problems because it discharges into the river channel. However, it is generally more expensive than any of the other types, except possibly some chute spillways on earth. The flip-up bucket is used in this country principally on massive hard-rock foundations. In Europe, this type of energy dissipater is extensively used on practically all rock foundations and on some low-head dams on soil foundations. The practice in this country is more conservative than the European practice relative to the design of energy dissipaters; therefore stilling basins are used extensively. Foundation requirements are similar to those for any gravity dam.

Side-channel spillways similar to Fig. 3 require extensive founda-

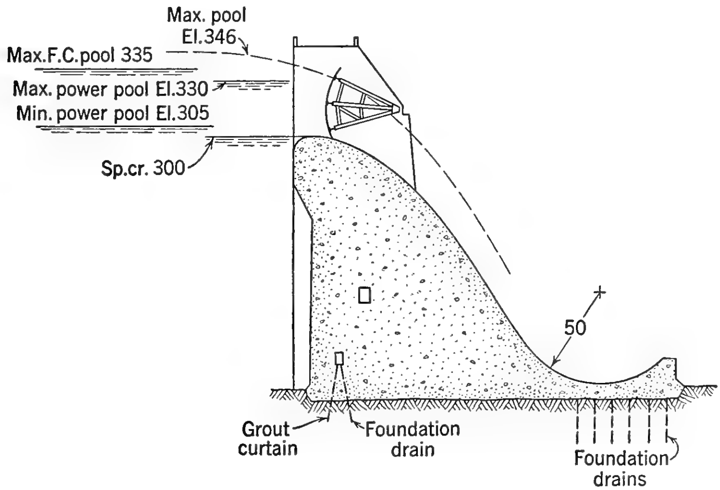

Fig. 1. Gravity spillway, Clark Hill Dam. Foundation is massive granite gneiss. Frequent operation.

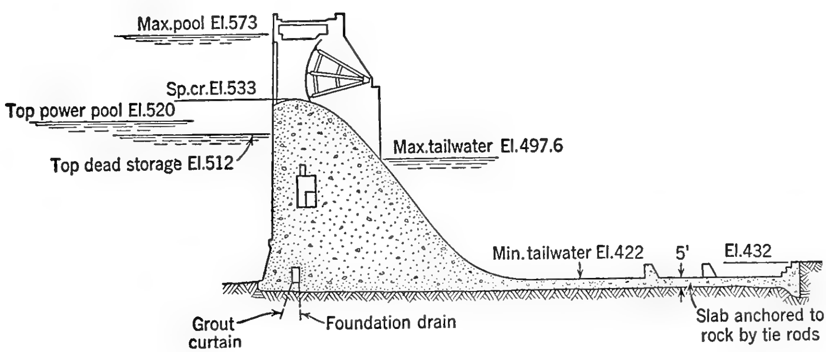

Fig. 2. Gravity spillway, Whitney Dam. Foundation is argillaceous limestone. Frequent operation.

tion investigations because their satisfactory performance depends to such a great extent on the stability of the rock. Deep cuts into the abutment are conducive to minor slides, and the steep side walls are subject to creep and spalling during construction. These minor geologic factors are difficult to evaluate from explorations, and as a result costly changes during construction are not unusual for this type of structure.

Chute spillways on earth as illustrated by Fig. 4 have been employed in a number of cases where rock was inaccessible at reasonable

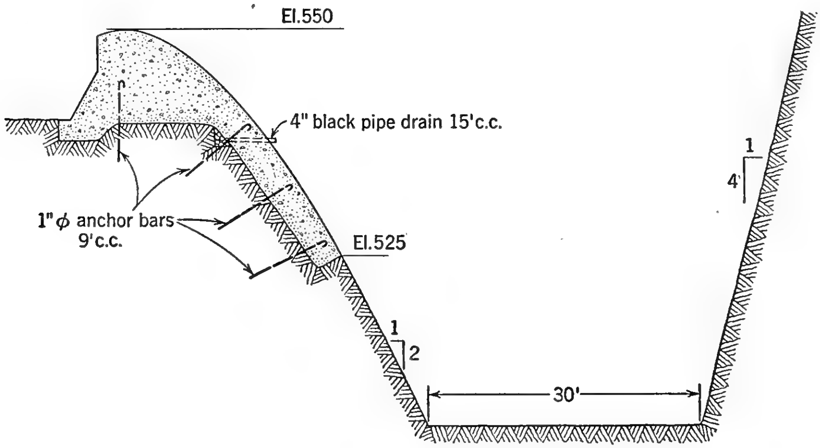

Fig. 3. Side-channel spillway, Surry Mt. Dam. Foundation is massive granite gneiss. Infrequent operation.

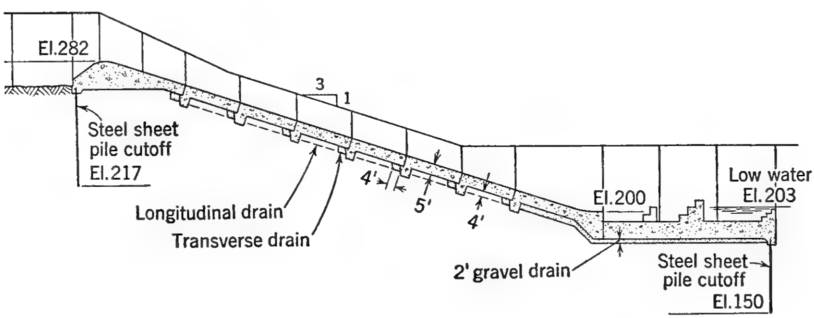

Fig. 4. Chute spillway, Sardis Dam. Foundation is soil and soft rock. Frequent operation.

depths. Foundation investigations for this type of spillway should be more extensive than for any other type. A cutoff along the center line of the weir section and an elaborate drainage system under the chute and stilling-basin portions are required. The shearing strength, compressibility, and expansion characteristics of the soil are important factors in design. Upheaval of concrete spillway slabs located on expansive formations such as the Bear Paw shale encountered at Fort Peck Dam presents a problem for further soil mechanics research. At Fort Peck the expansion of the shale foundation under the spillway chute and approach slabs due to release of load in the spillway cut has been extensive. Maximum upheaval in the center of the chute has been over 12 inches. Upheaval of the gate structure, which was constructed on caissons to a depth of 40 feet, has been nil.

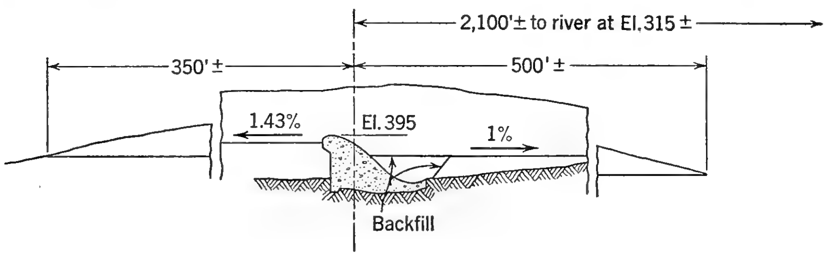

FIG. 5. Saddle spillway, Wappapello Dam. Foundation is hard, blocky limestone. Infrequent operation.

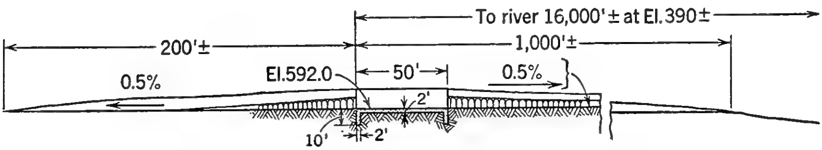

FIG. 6. Saddle spillway, Blakely Mt. Dam. Foundation is firm shale, highly folded. Infrequent operation.

Chute spillways are often founded on weak rock. Drainage under the chute section and stilling basin similar to that supplied for soil is generally required. Usually it is possible to anchor the slabs into the rock, thereby decreasing the chute and stilling-basin slab thicknesses over those required for soil. The upstream cutoff is usually in the form of a concrete key.

Saddle spillways without concrete pavement in the chute section are employed extensively where flow occurs infrequently. This type of spillway varies in design with foundation conditions and elevation of foundation rock in the saddle. At the Wappapello Dam (Fig. 5) a small ogee concrete section with a flip-up bucket was employed. At Blakely Mountain Dam (Fig. 6) a 50-foot paved section with a cutoff upstream and downstream forms the control. There are numerous cases where the rock itself is adequate for the control structure and no concrete weir or paving is required. There are also a few cases where a flat natural divide consisting of soil is used as a spillway. The Mosquito Creek Dam spillway is an example of this type. In this case no formal spillway structure was built.

EARTH DAMS

The two major foundation problems in earth dams are stability and permeability. Settlement of the dam proper is of concern only to the extent that adequate freeboard is maintained. A few consolidation tests, properly correlated with the observed settlement during the early stages of construction, will usually allow the establishment of a satisfactory gross grade. General geology of the site will prove most helpful in determining the most critical seepage and stability areas.

Stability of foundation soils is, with few exceptions, the determining factor in the design of the outer slopes of an earth dam. Explorations should be planned first to locate and outline the critical regions in the foundations. This can be accomplished adequately by disturbed-drive-sample methods by which satisfactory samples for classification and moisture determination can be obtained. After the critical areas have been outlined, large borings, 5 inches or more in diameter, should be made to obtain undisturbed samples of the silts and clays for shear and consolidation tests. Consolidated, drained, direct-shear tests are recommended for general use in determining the shearing strength of the materials under the induced loads. Triaxial compression tests are recommended for well-graded coarse-grained soils and for special studies. Consolidation tests are used to estimate the percentage of consolidation expected during construction. The shearing strength available at the critical period during construction is then determined on the basis of the percentage of the total consolidation that will have occurred. In places where only a small percentage of the total consolidation is expected to occur during construction, unconfined compression tests or unconsolidated undrained (UU) triaxial tests can be employed to determine the shearing strength. In all cases where consolidation is a factor in determining the shearing strength, piezometers should be installed to check the variations in pore pressures during construction. Open-ended pipes with a well point or sand pocket at the bottom are satisfactory for most foundations. Where more accurate measurements are required the Bureau of Reclamation type of hydrostatic pressure gage is recommended.

Measures for control of underseepage are seldom designed on the basis of adequate information. Natural soils vary widely in character in both vertical and horizontal extent and are often stratified. Extensive explorations are usually necessary to arrive at a reasonable estimate of permeability values. Positive cutoffs should be employed wherever feasible; therefore the exploration should first determine whether a cutoff is feasible along the center line or upstream of the center line. Borings made for this purpose should extend a sufficient depth into rock and be tested for water loss to determine if grouting of the rock will be required. If a cutoff is not practical, extensive explorations must be made upstream of the dam site to determine the extent and thickness of natural blanketing material and downstream to obtain foundation data for design of the required seepage-control measures. A row of deep borings at the downstream toe is required from which the effective size or relative permeability of each strata should be determined as a basis for relief-well design. In addition, borings should be made on several sections in order that continuity and extent of the pervious strata shall be outlined in the direction of flow.

CONSTRUCTION MATERIALS

The soils and geological survey of the site and surrounding area should develop the availability of (1) impervious and pervious materials for the embankment, (2) sand and gravel for drains and filter blankets, and (3) stone for riprap. In order to appraise properly the suitability of the local material, the soils engineer and the geologist should know how these materials will be used in the embankment. In the design of dams the terms *impervious* and *pervious* are employed in a rather broad sense to designate materials which are relatively impervious or pervious when compared with other materials in the dam and foundation. In the classification of different soils with regard to permeability, the following table may be used:

Impervious	K less than 0.01×10^{-4} cm. per sec.
Semi-impervious	K from $0.01–1.0 \times 10^{-4}$ cm. per sec.
Semi-pervious	K from $1.0–50 \times 10^{-4}$ cm. per sec.
Pervious	K from $50–500 \times 10^{-4}$ cm. per sec.
Very pervious	K greater than 500×10^{-4} cm. per sec.

A brief discussion of embankment sections and the use of these materials therein are given in subsequent paragraphs.

Depending on the availability of the relatively impervious material, the embankment may have a narrow central core such as employed on Sardis (Fig. 7), Mariposa (Fig. 8), and Franklin Falls (Fig. 12) dams, or a full impervious section as on Hulah Dam (Fig. 11). If there is

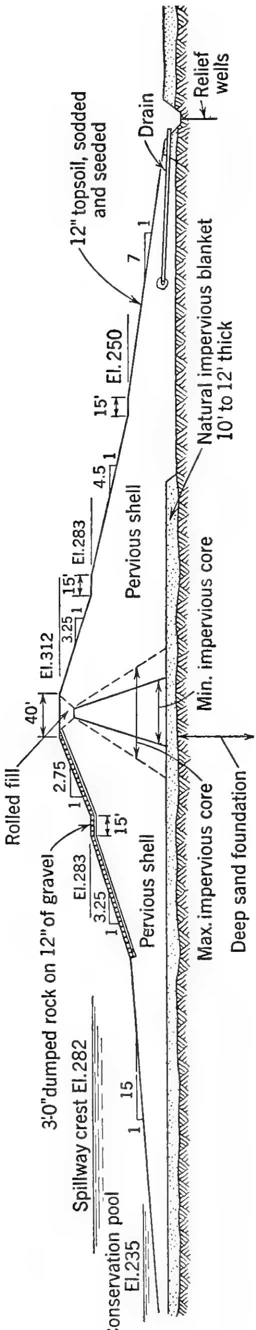

Fig. 7. Hydraulic fill, Sardis Dam, Little Tallahatchie River, Mississippi.

a reasonably equal distribution of impervious and pervious material, the impervious material might form the upstream half of the dam as in Cottage Grove (Fig. 9) and Great Salt Plains (Fig. 10) dams. These dams represent the more general cases in which the "impervious" zone consists of impervious or semi-impervious material as classified above. However, there are flood-control dams in which the shell materials are so coarse that semi-pervious material is used in the core. If loss of water is not a problem for consideration, the main criterion to be satisfied is that the core be tight enough to insure a low saturation line in the downstream portion of the dam. This is usually accomplished in a satisfactory manner if the downstream shell is 100 times more pervious than the core. In cases where the entire embankment is composed of impervious material, or where a satisfactory ratio of permeability cannot be obtained, drainage is used to lower the saturation line.

Pervious material is a most valuable asset at any earth-dam site. Extensive explorations are justified in locating possible sources for borrow areas. All types of pervious material from fine sand to gravel can be employed advantageously in the embankment section. Even sands generally classified as semi-pervious (silty or clayey sand) are relatively free-draining when compared with very impervious core materials and will, when properly placed in the dam, assure a low saturation line. Locally available coarse sands and gravels are usually economical for use as filter blankets and drains even when screening is necessary to meet a required gradation. Where foundation stability is not a problem, the most economical embankment sec-

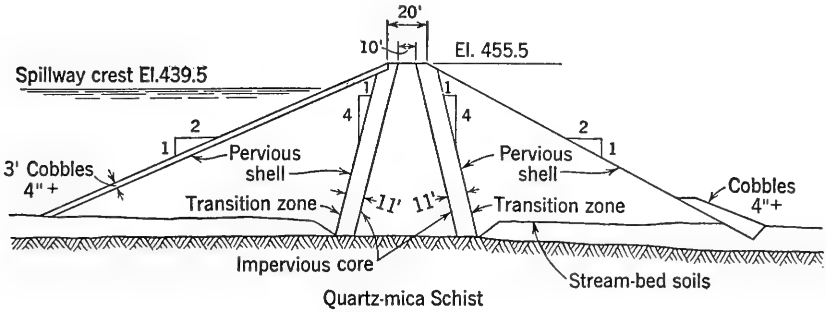

Fig. 8. Rolled fill, Mariposa Dam, Mariposa Creek, California.

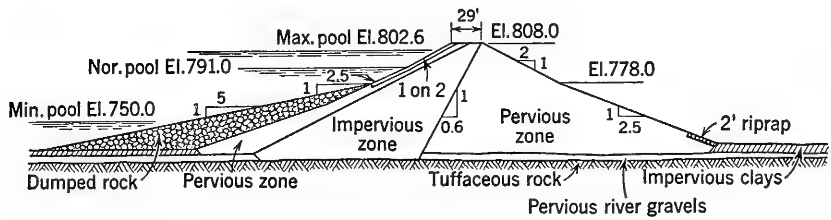

Fig. 9. Rolled fill, Cottage Grove Dam, Coast Fork, Willamette River, Oregon.

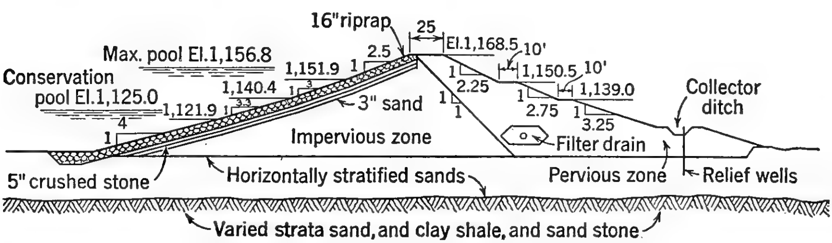

Fig. 10. Rolled fill, Great Salt Plains Dam, Salt Fork of Arkansas River, Oklahoma.

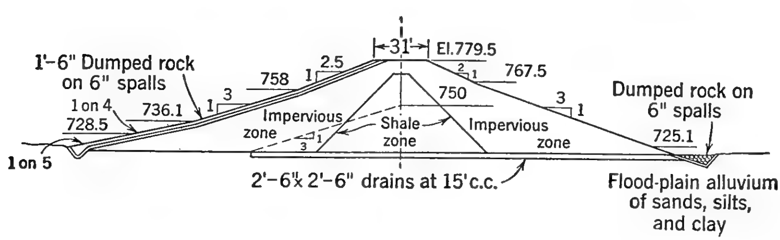

Fig. 11. Rolled fill, Hulah Dam, Caney River, Oklahoma.

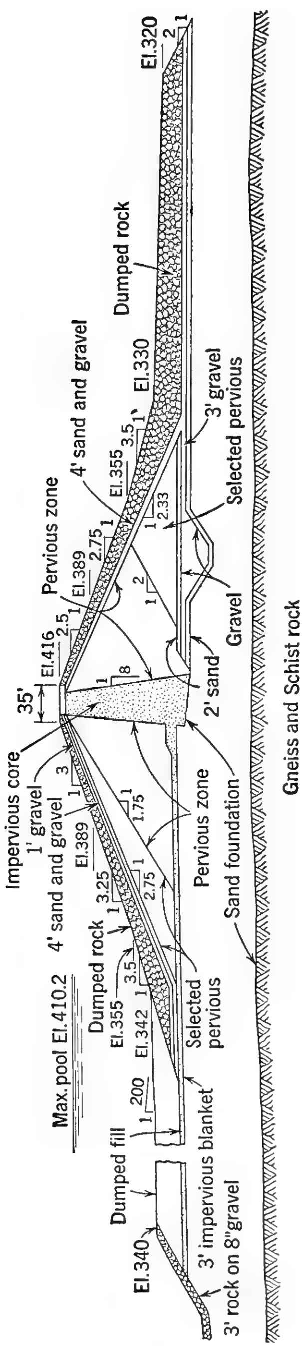

FIG. 12. Rolled fill, Franklin Falls Dam, Pemigewasset River, New Hampshire.

tion is one with a narrow central core with large sand and gravel shells. Recent large-scale triaxial tests have shown that the angle of internal friction for well-graded sand and gravel is about 45°. This high value of shearing resistance cannot be fully utilized, as it is not practical to construct on slopes steeper than 1 on $1\frac{1}{2}$ for angular gravels and about 1 on 2 for smooth, rounded gravels. The Mariposa Dam (Fig. 8) furnishes a good example of the economical use of such materials. The slopes are protected both upstream and downstream with large stones screened out of the main embankment fill.

Soils from required excavation can in most cases be employed in the embankment to economic advantage even though some processing is necessary, such as the crushing and mixing of the spillway excavation at the Youghiogheny Dam (Philippe, 1948). At the Fort Randall Dam the excess chalk rock excavating from the spillway and portal cuts was used in berms to reduce the main compacted dam section, and a heavy blanket of chalk was used on the upstream slope in place of costly riprap. A thick blanket of weathered granite, stripped from the aggregate quarry, was also used to replace riprap on the Clark Hill Dam.

Riprap for upstream slope protection is one of the most expensive features of earth-dam construction. Extensive field investigations are justified to locate the nearest source of satisfactory material. In a recent report, the Corps of Engineers (1948) gives results of a survey of riprap on more than thirty dams. The major findings of the survey are: a wide variety of rock, including some very soft formation, have proved successful; thinner riprap layers and correspondingly small stone can be used than have generally been employed for fetches not to exceed 10 miles; well-graded filter blankets are essential but may be relatively thin (6 to 12 inches). Required rock excavation, even though composed of relatively weak rock, can in most cases be used effectively in the upstream portion of the dam to reduce the quantity of required riprap.

EMBANKMENT DESIGN AND CONSTRUCTION

Stability of the embankment and foundation and seepage through the foundation are the principal design and construction problems that must be carefully considered by the soil mechanics engineer and geologist. Only a general summary of these problems will be given in this chapter because they have been adequately covered in other publications (Creager, Justin, and Hinds, 1945; Middlebrooks and Bertram, 1948; Middlebrooks, 1948).

Factors affecting embankment stability are directly or indirectly related to the shearing strength of the foundation and embankment. The most critical period in the construction of the dam is just before it is brought to grade or shortly thereafter. At this time, pore pressures, due to consolidation in the embankment and foundation, are at a maximum. If pore pressures do not develop, there is usually no question concerning the stability of the embankment, since most soils have adequate strength when fully consolidated.

The effect of rapid drawdown on the upstream slope deserves careful investigation. However, owing to the difficulty of accurately determining the degree of saturation that occurs during the filling period and the amount of drainage during the drawdown period, a detailed analysis is not usually justified. The method of analysis most generally employed on flood control dams is the instantaneous-drawdown method. A minimum safety factor of 1.0 is considered satisfactory in checking the slope stability for drawdown from maximum to minimum pool level. Where there is any doubt concerning the possibility of developing pore pressure during construction, piezometers should be installed in critical areas.

In the analysis of both upstream and downstream embankment slopes for stability during construction, a minimum safety factor of 1.50 is specified. For the stability of the upstream slope with reservoir empty and of the downstream slope with steady seepage from full reservoir head, a minimum factor of safety varying from 1.5

for clean granular materials to about 2.0 for highly cohesive clays is needed.

Most geologists may not be interested in the soil mechanics features that have been included in this discussion; however, they have been included to encourage greater interest in this field among geologists. It is considered most important in the design and construction of earth dams that the geologist at least understand the general principles of soil mechanics and that the soils engineer have a broader understanding of the effect of geological features on the application of the soil mechanics principles.

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CHAPTER 11

GEOLOGIC ASPECTS OF SOFT-GROUND TUNNELING

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A geological report on the site of a proposed earth tunnel should contain full information on all those known geological details and conditions which may conceivably influence the behavior of the ground in the tunnel during construction. From a scientific point of view, most of these details are likely to be irrelevant. Therefore a geologist will hardly be able to prepare an adequate report on the site of a proposed tunnel unless he is familiar with the factors that determine the tunneling conditions. This chapter contains general information concerning these factors. In the discussion of tunneling conditions it is necessary to make use of various elementary concepts which are associated with soil mechanics. (See Terzaghi and Peck, 1948; and Chapter 5 in this symposium.)

EFFECT OF STAND-UP TIME ON TUNNELING CONDITIONS

In connection with soft-ground tunneling, the difficulties and costs of construction of a tunnel with given dimensions depend almost exclusively on the *stand-up time* of the ground. The term stand-up time indicates the time that elapses between the exposure of an area at the roof of the tunnel and the beginning of noticeable movements of the ground above this area. The factors that determine the stand-up time of an unsupported roof area with given dimensions depend to a large extent on the position of the water table.

Above the water table, the stand-up time depends essentially on the tensile and shearing strength of the ground. Below the water table it depends not only on the strength of the soil but also on its average permeability and, to a large extent, on the degree of continuity of the most permeable members of the formation. A lens of water-bearing sand in a silt stratum may be perfectly harmless; a continuous layer of the same sand may give rise to a "blow," and, if this layer communicates with a large body of water-bearing sand within a short distance from the tunnel, a catastrophe may result.

TUNNEL MAN'S GROUND CLASSIFICATION

Unconsciously using the concept of the stand-up time as a criterion, the tunnel man distinguishes between six principal categories of "ground," namely, firm, raveling, running, flowing, squeezing, and swelling ground.

In *firm ground* the tunnel heading can be advanced without any roof support, and the permanent lining can be constructed before the ground will start to move. Typical representatives of firm ground are loess above the water table and various calcareous clays with low plasticity such as the marls of South Carolina.

In *raveling ground* chunks or flakes of material begin to drop out of the roof or the sides some time after the ground has been exposed. If the process of raveling starts within a few minutes, the ground is *fast-raveling.* Otherwise it is referred to as *slowly raveling.* Fast-raveling conditions are likely to be encountered in residual soil or in sand with a clay binder located below the water table. Above the water table the same soils may be slowly raveling or even firm.

In *running ground* the removal of the lateral support on any surface rising at an angle of more than about 34° to the horizontal is followed by a "run," whereby the material flows like granulated sugar until the slope angle becomes equal to about 34°. Running conditions prevail in clean, loose gravel and in clean, coarse or medium sand above the water table. In clean, fine, moist sand the run is preceded by a brief period of raveling. A ground with such behavior is *cohesive-running.*

Flowing ground moves like a viscous liquid. In contrast to running ground, it can invade the tunnel not only through the roof and the sides but also through the bottom. If the flow is not stopped, it continues until the tunnel is completely filled. The rush of flowing ground into a tunnel is sometimes referred to as a *blow.* Flowing conditions prevail in any ground with an effective grain size in excess of about 0.005 millimeter, provided that the tunnel is located below the water table. Above the water table the same ground has the character of a raveling or running ground.

Squeezing ground slowly advances into the tunnel without any signs of fracturing and without perceptible increase of the water content of the ground surrounding the tunnel. Although the squeeze may not even be noticed, the loss of ground due to squeeze may be important enough to produce a conspicuous trough-like subsidence of the ground surface above the tunnel. Squeezing conditions are met with in every tunnel through soft or medium clay.

Swelling ground, like squeezing ground, moves slowly into the tunnel, but the movement is associated with a very considerable volume increase of the ground surrounding the tunnel. Swelling conditions are likely to develop in tunnels through heavily precompressed clays with a plasticity index in excess of about 30, and in sedimentary formations containing layers of anhydrite.

PROCEDURES FOR CHANGING GROUND CONDITIONS IN TUNNELS

All the serious difficulties that may be encountered during the construction of an earth tunnel are directly or indirectly due to the percolation of water toward the tunnel. Therefore most of the techniques for improving the ground conditions are directed toward stopping the seepage.

In cohesionless or slightly cohesive ground, such as clean or silty sand, a mixture of soil and water enters the tunnel through every gap in the lining. Such "flows" or "blows" can be avoided by three different means. The water table can be lowered to a level located below the bottom of the tunnel by drainage; the tunnel can be filled with compressed air under a pressure equal to the water pressure at the bottom of the tunnel, or the voids of the ground surrounding the tunnel can be clogged by the injection of suitable materials such as cement or mixtures of chemicals.

The water that occupies the voids of a porous material above the water table is retained in the voids by capillary forces. (See, for instance, Terzaghi and Peck, 1948, pp. 115–129.) Hence, if the water table is lowered by drainage to a level below that of the bottom of the tunnel, the water ceases to percolate toward the tunnel, though the voids of the ground may remain almost or entirely filled with water. Drainage changes flowing ground into raveling or running ground which can easily be handled.

Another method of improving the properties of soft ground involves the use of compressed air. The principle of this method is illustrated by Fig. 1. Figure 1*a* is a vertical section through the heading of a tunnel in flowing ground. The tunnel is filled with compressed air under a pressure equal to the water pressure at the bottom of the tunnel. In Fig. 1*b* the horizontal distances between *ac* and *ab* represent the pressure in the water which occupies the voids of the ground. Since the air pressure on the heading is greater than the water pressure, the compressed air not only stops the flow of water into the tunnel, but it also tends to drive the water out of the voids away from the tunnel. The rate at which the water is displaced depends on the air pressure and on the effective size D_{10} of the soil particles. The value of D_{10} indicates that 10 percent of the total dry weight of the soil

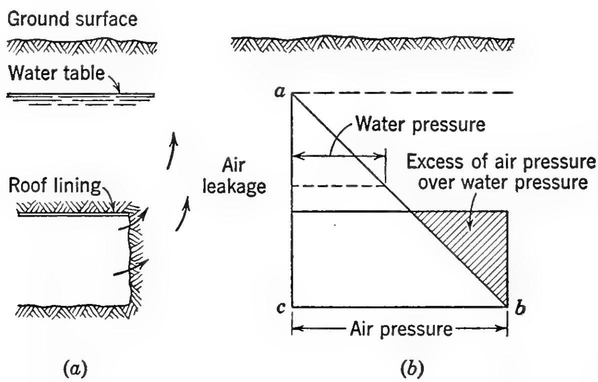

FIG. 1. Diagram illustrating the principle of tunneling with compressed air.

consists of particles with a grain size equal to or smaller than D_{10}.

If D_{10} of the soil particles is smaller than about 0.01 millimeter, the rate of displacement is likely to be zero, because the surface tension of the water may prevent the air from entering the voids. If D_{10} is greater than about 0.01 millimeter, the rate of displacement rapidly increases with increasing D_{10}; if D_{10} is greater than about 0.2 millimeter, it becomes so high that a considerable quantity of air leaks out of the tunnel. Under such conditions the miners are compelled to plaster the joints in the temporary tunnel support and part of the exposed surfaces of the ground with mud to reduce the loss of air. If the heading strikes an exceptionally permeable layer, the air pressure in the tunnel may suddenly drop to zero, whereupon the tunnel is flooded. Such an accident is known as a *blowout.* In unconsolidated deposits with an erratic structure, the danger of a blowout is considerably greater than in regularly stratified ones, because they do not contain continuous layers of relatively impermeable material which interfere with the formation of air channels leading from the heading toward the water table.

In fine-grained soils such as silt or soft clay or in mixed-grained soils with a silt or clay matrix, the air does not enter the voids at all. These soils are changed by compressed air from flowing or rapidly squeezing into raveling or slowly squeezing ground. The reason is illustrated by Fig. 2, representing a vertical section through the center line of a tunnel in soft clay. The clay tends to flow along a curved surface of sliding *ab* into the tunnel. This tendency is due partly to the weight of the clay located above *ab* and partly to the seepage pressure exerted by the water which percolates toward the heading. Compressed air under a pressure equal to the water pressure at the level of point *b* not only stops the seepage as shown in Fig. 1, but it also resists the tendency of the solid clay particles to descend toward the heading.

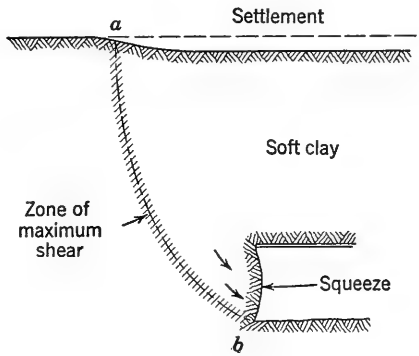

FIG. 2. Diagram illustrating the cause of the "squeeze" in tunnels through soft clay. The clay moves slowly along *ab* toward the heading.

A third possibility for improving the ground conditions in earth tunnels consists in clogging the voids of the ground surrounding the tunnel by grouting. So far this method has been used only for reducing air leakage through gravel strata and for reinforcing the ground located between the roof of shallow tunnels and the base of foundations located above the roof (Harding and Glossop, 1940).

The limits which nature has imposed on the successful application of the different methods for improving the ground conditions in earth tunnels are discussed below in the section on "Methods of Soft-Ground Tunneling."

TREATMENT OF SWELLING GROUND

Even a very dangerous swelling ground may behave like a firm ground at the heading. However, a few hours or days after exposure the ground begins to advance toward the tunnel, and the ground movement continues until the tunnel is closed up, unless the movement is stopped by the construction of a tunnel support. The movement is associated with a considerable increase of the volume of the material surrounding the tunnel. After the tunnel support is erected and backfilled, the swelling ceases; but the pressure on the support increases first at an increasing, later at a decreasing, rate, and it approaches an ultimate value which may be considerably greater than the overburden pressure. In tunnels through clay this is not possible unless the initial horizontal pressure in the clay is considerably greater than the vertical pressure. The most common cause of such stress conditions is intense compaction under the weight of superimposed strata which are subsequently removed by erosion.

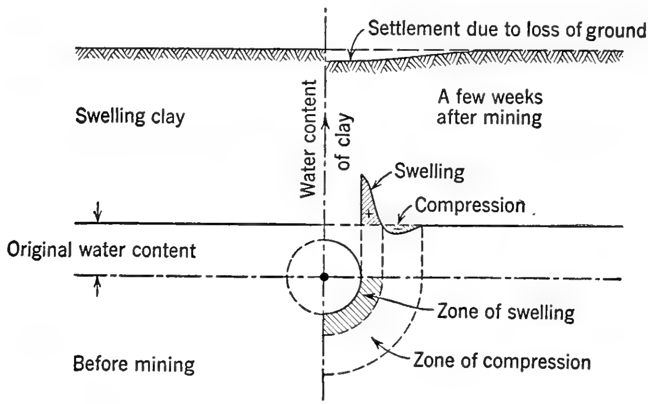

FIG. 3. Diagram illustrating the mechanics of the swelling of stiff clay in a tunnel. The change in the distribution of the water content caused by the mining operations is shown on the right-hand side.

According to a widespread belief the water that causes the swelling comes out of the air contained in the tunnel. Therefore many attempts have been made to prevent the swelling by covering the exposed surfaces in tunnels with a bituminous coating. Most of these attempts have failed because, as a rule, the water that causes the swelling comes out of the ground and not out of the air. The mechanics of this process is illustrated by Fig. 3. The left-hand side of the diagram shows the distribution of the water content of the clay over a horizontal section through the center line of a proposed cylindrical tunnel in a heavily precompressed clay prior to excavation. Excavation relieves the confining pressure on the clay adjoining the walls of the tunnel. According to the theories of soil mechanics, local removal of the load on a saturated porous material draws water out of the loaded portions of the material toward the zone of pressure relaxation. In the tunnel the zone of pressure relaxation has the shape of a cylindrical mantle surrounding the tunnel bore. On account of the pressure relaxation, water is drawn toward this zone out of the clay located at a greater distance from the tunnel. Therefore the water content of the clay adjoining the walls of the tunnel increases and the clay swells, whereas beyond this zone the water content decreases. On the right-hand side of Fig. 3 this change of the water content is indicated by shaded areas.

The theory illustrated by Fig. 3 has been verified repeatedly by the results of water-content determinations on samples from the proximity of the walls of tunnels in the "Argile plastique" of the region of Paris, France, a stiff Eocene clay with a plasticity index of 60 to 80 percent. The clay is similar in many respects to the London clay. It rests on the Cretaceous shales of Meudon. It is overlaid by Eocene limestones, and the entire formation is gently folded. The thickness of the clay stratum varies between about 100 and 200 feet. The state of precompression was produced by the weight of superimposed Tertiary and younger strata which were later removed by erosion. The temporary load due to the weight of these strata was of the order of magnitude of 25 tons per square foot. A general description of the physical properties of the clay was published by Langer (1936). One of the subway tunnels of Paris was excavated in this clay. The average initial water content of the clay was 56 percent. Within a few weeks after exposure the water content of the clay at the walls of the tunnel had increased to values between 90 and 130 percent. With increasing distance from the walls the water content decreased, and it had a minimum of 46 percent at a distance of about 13 feet from the walls (observations by Langer, reported by Terzaghi, 1936).

Because the water that causes the swelling of stiff clay comes out of the clay, the swelling of the clay can be prevented only by a tube-shaped tunnel support which is strong enough to sustain the swelling pressure. However, the ultimate pressure on the tube can be reduced considerably by providing a clearance between the walls of the tunnel bore and the extrados of the tunnel support, or else by using tunnel supports which can yield considerably under pressure without being crushed. Experience indicates that a clearance of about 6 inches commonly serves the purpose. A description of the different systems of yielding steel supports used in Belgian and German coal mines for reducing the ultimate load on the supports was given by Ernould (1934).

Application of a watertight coating can do no more than prevent relatively harmless surface processes such as the raveling of jointed clay or shale due to desiccation.

METHODS OF SOFT-GROUND TUNNELING

The methods used in constructing an earth tunnel must be adapted to the stand-up time t_s of the ground and to the performance of the ground during the process of mining. The following paragraphs contain a brief review of the methods, illustrated by Fig. 4.

In firm ground, with a stand-up time t_s of more than about one day, no temporary support is required (Fig. 4*a*). In raveling ground with a t_s value between 1 day and 5 minutes and in squeezing ground, steel liner plates are mined in, one by one, and assembled into rings or "courses" as shown in Fig. 4*b*. This can be done without giving the ground an opportunity to move. The face does not require any lateral support. In cohesive running or running ground, the leading edge of the roof and side support must be kept ahead of the excavation. This is accomplished by means of "poling boards" or "poling plates" (Fig. 4*c*). The face must be supported by means of breast boards. As excavation proceeds, the breast boards are carried forward, one by one, over a distance equal to the width of one course of liner plates, starting at the crown.

Really serious difficulties are encountered only in flowing ground. It appears that the problem of mining through flowing ground was not adequately solved until the beginning of the nineteenth century, when coal-mining operations were started on a large scale. The technique that was developed under the pressure of necessity is illustrated by Fig. 4*d*. The roof and the sides are supported by "poling boards" which are driven at a slight angle to the center line of the tunnel. The face is breasted, and the tunnel bottom is covered with a timber floor strong enough to prevent a heave of the ground located beneath the tunnel. The procedure calls for expert carpenters, because no open joints between boards can be tolerated. "Where the material is very bad only small openings should be made and while one miner is making it, another must stand ready with hay and filling material to stop the hole as soon as enough ground has, for the time, been admitted; this stopping must often be done while the man is splashed over with the pouring mass and standing knee-deep in it, groping with his eyes shut to perform his task. It is hardly necessary to say that none but the best and most reliable workmen can be depended on to show the requisite coolness and dexterity at the right moment" (Drinker, 1878). In spite of skill and utmost precaution, catastrophes can not always be avoided, and under difficult conditions the progress slows down to 1 foot per week, two twelve-hour shifts per day.

On account of the costs and hazards involved in mining through flowing ground, the attempts to simplify the procedure started very early. They led to various refinements of the methods of drainage and, as early as the middle of the nineteenth century, to the invention of the compressed-air and the shield methods of tunneling.

The original method of draining the ground surrounding a large

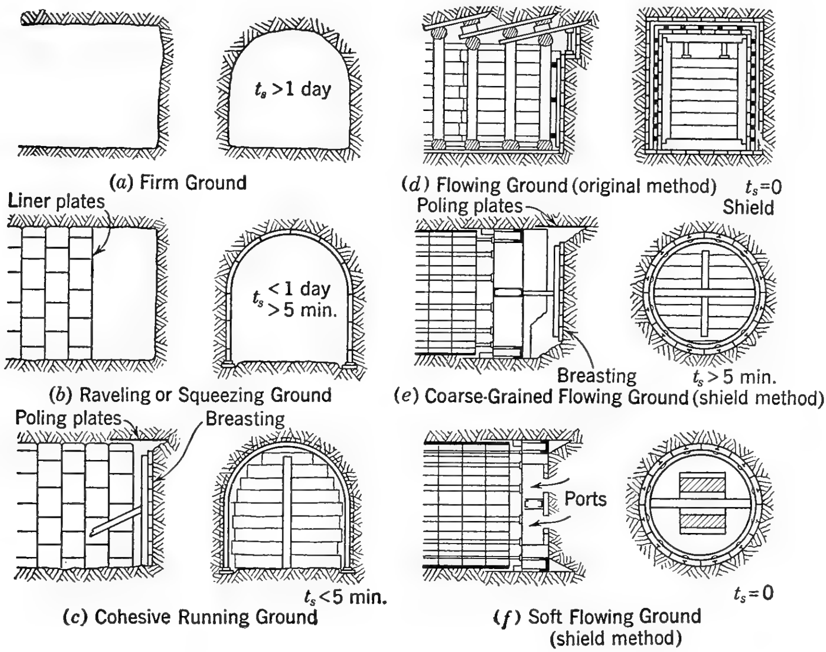

FIG. 4. Principal types of temporary tunnel supports.

tunnel by means of drainage galleries located on both sides of the tunnel was superseded by pumping from filter wells or wellpoints. The wells are drilled on both sides of the tunnel from the surface of the ground to a depth of 10 or 15 feet below the bottom of the tunnel, or else they are installed on the bottom of the tunnel. New wells are drilled as the heading advances. Both procedures have been successfully used on tunnel jobs. However, drainage by pumping from wells is impracticable unless the effective grain size D_{10} of the most permeable layers in the ground surrounding the tunnel is greater than about 0.05 millimeter. Under exceptional conditions, finer soils can be drained by means of the vacuum or electro-osmotic method (Terzaghi and Peck, 1948, pp. 337–340).

The function of the compressed air in tunnels is illustrated by Fig. 1.

Compressed air under adequate pressure has the same beneficial effects as successful drainage. It transforms flowing into running, raveling, or slowly squeezing ground. If the air pressure is lower than about 18 pounds per square inch, corresponding to a head of water of 36 feet, the compressed air has no detrimental physiological effects. If the air pressure is increased beyond 18 pounds per square inch, its effects on the human organism become more and more harmful; the number of working hours per shift must be reduced; at the same time the wages per shift go up, and an air pressure of about 50 pounds per square inch, corresponding to a head of water of 100 feet, is the highest the organism of a normal person can stand. Hence the use of compressed air is limited to tunnels located at a depth of less than 100 feet below the water table. Furthermore, the use of compressed air requires the installation of a compressor plant and of airlocks, which are expensive. For this reason, in short tunnels or when a tunnel is driven over a short distance through flowing ground, it may be more economical to drain the ground, to consolidate the ground ahead of the working face by means of injections, or, as a last resort, to try the original procedure for mining through flowing ground, shown in Fig. 4*d*.

The shield method of tunneling is illustrated by Figs. 4*e* and 4*f*. A shield is merely a ring-shaped biscuit cutter which is shoved ahead by means of hydraulic jacks. If the shield travels through coarse-grained flowing ground, it is necessary to transform the flowing into running or raveling ground by means of compressed air. The ground must be excavated ahead of the shield, the roof located beyond the cutting edge must be supported by poling boards or other convenient means, and the face must be breasted as shown in Fig. 4*e*.

In a shield tunnel the pressure on the breast boards can easily be transferred onto the heavy steel beams that subdivide the central opening into smaller panels. Furthermore if a run or a blow occurs, the miner has at his disposal ready-made supports against which he can brace his emergency bulkheads. However, a shield is very expensive, and the shield method of tunneling requires a very much heavier temporary lining than does the method of hand mining, because the lining must be strong enough to sustain the heavy longitudinal pressure exerted by the jacks. Hence, if the ground conditions call for excavation ahead of the shield, it is commonly more economical to construct the tunnel without the assistance of a shield.

In soft, flowing ground such as river silt, no excavation ahead of the shield is required. It suffices to push the shield ahead by means of hydraulic jacks. The ground ahead of the shield is displaced and enters the tunnel through the portholes shown in Fig. 4*f*. This procedure is very economical because it permits rapid progress and it practically eliminates tunneling hazards. Therefore, nowadays, long tunnels through soft, flowing ground are seldom constructed without the use of a shield.

SUBSOIL EXPLORATION

Reliable information on the subsoil conditions can be obtained only by means of test borings. The methods for making the borings were developed in connection with the exploration of coal measures, and they are more than a hundred years old. However, up to the beginning of the twentieth century, soil samples were secured by means of tools, such as augers or mudpumps, which destroy the structure of the soil and change its consistency. In tunnels the behavior of sediments with similar grain-size characteristics and mineralogical composition varies greatly with their porosity and water content and with the details of stratification. A varved clay, for instance, is likely to soften much more rapidly than a homogeneous clay with equal average water content. Hence, in connection with the subsoil exploration for earth tunnels, relatively undisturbed samples should be secured by means of one of the many sampling devices developed during the last decades. A complete report on the present status of the technique of sampling is being prepared by the Soil Mechanics Division of the American Society of Civil Engineers.

The amount of information that can be derived from the results of the test borings is limited by the fact that it is seldom practicable to make more than one boring for every hundred feet of the length of the tunnel. Furthermore, if compressed air is to be used, borings should only be made well beyond the horizontal boundaries of the space to be occupied by the tunnel. Thus the test borings furnish information only on the sequence of the strata along a few vertical lines, widely separated and located beyond the boundaries of the tunnel. On the basis of this fragmentary information, the investigator is compelled to construct a continuous geologic profile through the center line of the tunnel. The results of this operation can be very misleading, unless the geologic structure is very simple or the profile is prepared by an experienced geologist and is accompanied by a report dealing with the possible differences between profile and reality. A thorough investigation of the unpredictable variations of the soil properties between drill holes was made during the construction of the subway of Chicago (Terzaghi, 1943).

POSITION OF THE WATER TABLE

At the beginning of this chapter it was shown that the working conditions in tunnels through sediments of any kind other than silt and clay depend primarily on the position of the water table with reference to the bottom of the tunnel. Therefore the second prerequisite for a reliable forecast of tunneling conditions consists in securing conclusive information regarding the position of the water table.

Even today it is by no means uncommon that the position of the water table is inferred from the height to which the water rises in the drill holes between shifts. A conclusion arrived at on such a basis can

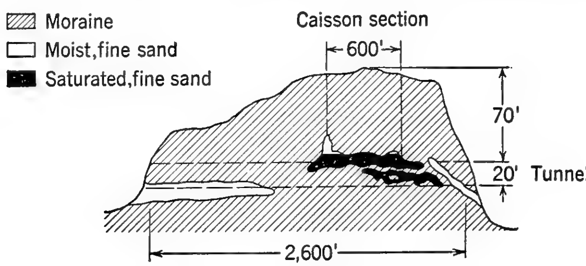

FIG. 5. Geological section through a terminal moraine in northern Switzerland, along the center line of the Emmersberg Tunnel. (After *Schweizer Bauzeitung,* 1895, p. 135.)

be utterly misleading, because in sand it may take only a few hours whereas in silt or clay formations it may take several weeks or years for the water level in the drill hole to arrive within a few inches of the position of the water table. The practical consequences of erroneous conceptions regarding the position of the water table are illustrated in Figs. 5 and 6.

Figure 5 is a section across a terminal moraine along the center line of the Emmersberg Tunnel in northern Switzerland. The tunnel has a length of about 2,600 feet, and the crest of the moraine is located at an elevation of about 70 feet above the roof of the tunnel. The moraine consists of a dense mixture of rock fragments, grit, and rock flour. It contains large, irregular lenses of very fine sand which do not communicate with each other. Since the permeability of the surrounding moraine material is very low, the water table in the sand lenses is located at very different elevations. Some of the lenses do not contain any free water at all. In the first lenses that were encountered, the sand was only moist. As a consequence it was so stable that no breasting was required. However, as soon as the heading arrived at the first wet pocket, the sand exhibited the character of flowing ground. Large quantities of sand mixed with water invaded the tunnel. Sinkholes appeared on the ground surface above the tunnel. When attempts were made to continue the mining operations in the tunnel under compressed air, the disturbance of the ground surrounding the tunnel was already so far advanced that the attempts failed,

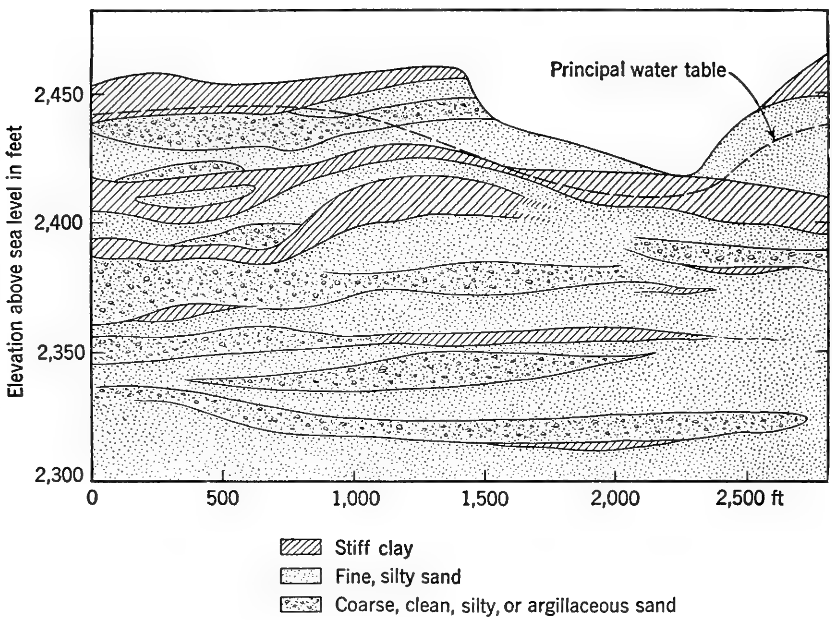

FIG. 6. Geological section through a valley in the city of São Paulo, Brazil. The strata are part of a Tertiary delta formation and the relief is believed to be post-Pliocene. (After E. Pichler.)

and it was decided to finish the job by means of a series of compressed-air caissons which were carried down from the ground surface to the level of the bottom of the tunnel (*Schweizer Bauzeitung*, 1894–1895).

Figure 6 is a simplified geological section through one of the districts of the city of São Paulo in Brazil. The city is located on Tertiary deposits which appear to have been formed by an aggrading, meandering river. As a result of a lowering of base level, the river deposit was dissected to a depth of at least 100 feet below the original elevation of the valley floor. The sediments consist of stratified layers of clay, silt, and silty sand and gravel. In horizontal directions there are imperceptible transitions from one stratum into another. Therefore the position of the water table is not well defined. When a hole is drilled, the water is likely to rise from different strata to different elevations. The water table marked "principal water table" is the approximate locus of the points to which the water rises in drill holes from most of the strata.

A few years ago a municipal waterworks tunnel was built within the city limits. The tunnel is 9 feet wide and high and about 1,500 feet long. The bottom of the tunnel is located about 100 feet below the street surface and 50 feet below the principal water table. The outer parts of the tunnel, between the portals and the two ends of the middle portion, with a length of about 500 feet, are located in water-bearing, fine to medium sand with some clay.

The tunnel was started as a free-air, hand-mined tunnel with timber supports. However, the ground moved so rapidly into the tunnel and the street surface settled so badly that air locks were installed. As the ground was already badly disturbed, the loss of air was excessive. Therefore the contractor did not succeed in drying up the bottom, and it was necessary to use forepoling and to breast the working face. The loss of ground was about 50 percent, and the buildings located above the tunnel settled by amounts up to 8 inches. The middle part of the tunnel, with a length of about 500 feet, is located in stiff, yellow clay. No difficulties were encountered in this section.

In view of the decisive influence of the position of the water table on tunneling conditions, no guesswork regarding this position should be tolerated. If the subsoil contains continuous layers of fairly clean sand or gravel, sufficiently reliable information concerning the groundwater conditions can be obtained by transforming the drill holes into observation wells and by keeping a record of the variations of the water level in these holes. If the subsoil consists of silty sand or silt, it is necessary to install in the drill holes piezometric tubes with a diameter of less than half an inch. Such tubes have been successfully used for observing the rise of the piezometric surface for a silty stratum due to the weight of a superimposed fill (Casagrande, 1949). However, if the ground surrounding the site of a proposed tunnel consists only of fine silt or clay, no accurate information regarding the water table is required, because the performance of these sediments in the tunnel depends only on their water content and consistency.

FUNCTIONS OF THE GEOLOGIST IN EARTH-TUNNEL JOBS

The foremost duties of the geologist on an earth-tunnel job are the construction of a geological profile along the center line of the proposed tunnel, based on the results of the test borings; selection of suitable sites for supplementary borings which are needed for eliminating the most objectionable uncertainties involved in the construction of the profile; and correlation of the results of the ground-water observations with the geologic structure of the site.

On the basis of the results of a general geologic survey of the region surrounding the tunnel site, of a visual inspection of undisturbed samples, and of the soil tests performed by the engineer, the geologist ascertains the origin of the strata which were encountered in the test borings. In accordance with his findings he designates the strata as river, flood-plain, shore, lake, marine, glacial, fluvioglacial, wind-laid, or composite deposits. The next step is to construct a geological profile which is compatible with the geological origin of the strata. On account of his knowledge of the structure of sedimentary deposits, the geologist will be in a position to pass competent judgment on the degree of accuracy of the profile. In the report attached to the profile he will also inform the engineer about the possibility or probability of significant deviations from the profile such as the existence of pockets of water-bearing sand or of buried channels which were not encountered during the boring operations.

Finally, the geologist should carefully examine and comment on the data that have been secured regarding the ground-water conditions and correlate them with the geological structure of the site. If there are indications of the existence of one or more perched water tables or of artesian conditions, not clearly revealed by the records, he should insist on the installation of all those supplementary observation wells or piezometric tubes which are necessary to clarify controversial issues.

The effects of geological details on tunneling conditions depend entirely on the physical properties of the sediments and on the interaction between solid and water. Therefore the geologist will hardly be able to render satisfactory services on a tunnel job unless he knows the fundamental principles of soil mechanics. The geologist should also be acquainted with the techniques of boring and sampling and with the sources of the manifold errors that may enter into test boring records. On the other hand the engineer will hardly realize the uncertainties involved in the construction of geological profiles and the benefits he can derive from competent geological advice unless he is familiar with the elements of physical geology. Hence an active interchange of information between the two professions is urgently needed.

TOPICS FOR FUTURE RESEARCH

The most important subjects for future research activities in the field of soft-ground tunneling are the details of the structure of sedimentary deposits, the behavior of different sediments at tunnel headings, and the loads on temporary and permanent tunnel supports.

A great deal of time and labor has been devoted by geologists to an investigation of the different processes of sedimentation, but the products of sedimentation have received relatively little attention. We need systematic collections of geological profiles showing the structural patterns which are produced by different processes of sedimentation. These patterns can be seen only on the slopes of open cuts, immediately after excavation, on the slopes of sand, gravel, and clay pits, and at the headings of tunnels during construction. Familiarity with such patterns would discourage the engineer from constructing geological profiles without the assistance of a geologist, and it would help the geologist in the interpretation of test boring records.

The behavior of different sediments at tunnel headings can be learned only from personal experience, which is inevitably limited, and from case records accompanied by an adequate description of the geology of the tunnel site. Yet, up to this time, very few records of earth tunnels have been published, and in most of the published ones adequate geological information is conspicuous by its absence.

The measurement of the load on tunnel supports is needed as a check on our methods of estimating the loads in advance of construction. Extensive observations of this kind were made during the construction of the subway in Chicago (Terzaghi, 1942, 1943). Equally important is quantitative information about the pressure exerted by swelling ground on rigid and yielding tunnel supports, because this pressure can be estimated only on the basis of precedents. Measurements of swelling pressures were carried out in various tunnels in the "Argile plastique" of the region of Paris (Langer, quoted by Terzaghi, 1936). At present, similar measurements are being made in coal mines in southern Holland (according to a personal communication received by the author from Mr. J. M. Hermes, Staatsmijn Emma, Treebeek, Holland), and, by the U. S. Army Engineers, in an experimental tunnel at the site of the Garrison Dam in North Dakota.

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Chapter 12

SEDIMENTARY GEOLOGY OF THE ALLUVIAL VALLEY OF THE LOWER MISSISSIPPI RIVER AND ITS INFLUENCE ON FOUNDATION PROBLEMS

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ALLUVIAL DEPOSITS

Alluviation in the Lower Mississippi Valley

The most important recent geological influence on Mississippi River behavior has been the advance and retreat of continental glaciers. It has been estimated, and relatively accurately because the terminal moraine outlines are fairly well known, that 20 million square miles of land surface were covered by ice at its maximum extent. The estimates of thickness of this great ice cap are not in such common agreement, but a figure of 1 mile for average maximum thickness is often given. This would represent a volume of 20 million cubic miles of landlocked water. Theoretically, such a vast volume when removed from the ocean basins would be sufficient to lower sea level somewhere in the neighborhood of 450 feet, even if allowance is made for the present-day ice masses which have not yet been melted. With sea level at such a considerably lower stand during times of glaciation (Daly, 1929), the Mississippi River was flowing with an overly steep gradient and thus eroded deeply into its valley. But, with the rise of sea level during waning of glaciation and the consequent loss of gradient along the Mississippi River's course, alluviation of its former incised valley took place.

Since continental glaciation has occurred during five distinct times, there are an equal number of such alluvial deposits in the Lower Mississippi Valley. These are in the form of the modern Alluvial Valley fill plus four distinct terraces, which are recognized according to their individual elevations (Fisk, 1944). The oldest of these terraces has the highest topographic expression, whereas the remainder have progressively lower elevations in order of decreasing age. This condition has resulted from a progressive continental uplift which has raised the deposits vertically, thus protecting portions of them from removal by subsequent erosive action of the Mississippi River. Their present areal expression is that of strips bordering the modern Alluvial Valley and elongated "islands," such as Crowley's Ridge, which divide its northern portion. Southward, in southern Louisiana, these terrace formations have been downwarped as a result of sinking in the Gulf Coast geosyncline and plunge under Recent deposits of the Mississippi deltaic mass.

The areal distribution of these sedimentary units in relation to the modern Mississippi River and to physiographic basins and ridges within its valley is illustrated in Fig. 1.

Each of the terrace deposits reflects a sequence of deposition which, as a result of lesser modification by erosion, is ideally shown in the Recent alluvial fill. During its last period of overly steepened gradient, the Mississippi River transported very coarse loads containing much gravel, derived chiefly from adjacent Paleozoic upland areas. However, with the slow decrease in gradient resulting from gradually rising seas, much of this coarse load was deposited, thus forming the present valley fill. Eventually, the Mississippi River's gradient slackened to such a point that gravels were no longer being transported, although alluviation was continuing with further advances in sea level. Under these circumstances, the alluvial deposits were formed of finer materials, mostly sands.

Thus it can be seen that, on the whole, the Recent alluvium can be divided sharply into two types: (1) the lower graveliferous section and (2) an upper, essentially non-graveliferous section.

In the graveliferous section, about 95 percent of all samples contain some gravel; in the non-graveliferous section, less than 1 percent of the samples show any gravel whatsoever. In general, the graveliferous section contains gravels somewhat in excess of 25 percent by weight, the remainder being coarse sand. On the other hand, some parts of the graveliferous section may contain only fine- or medium-grained sands with little or no gravel. In general, the cobbles, where present, are larger at depth and smaller in the shallower layers. It is common, north of the Louisiana-Arkansas boundary, to find occasional cobbles 1 foot in diameter, but southward there is a rapid decrease in size, so that in Louisiana it is uncommon to find specimens over 3 inches in diameter, and toward the coast gravel over 1 inch in diameter

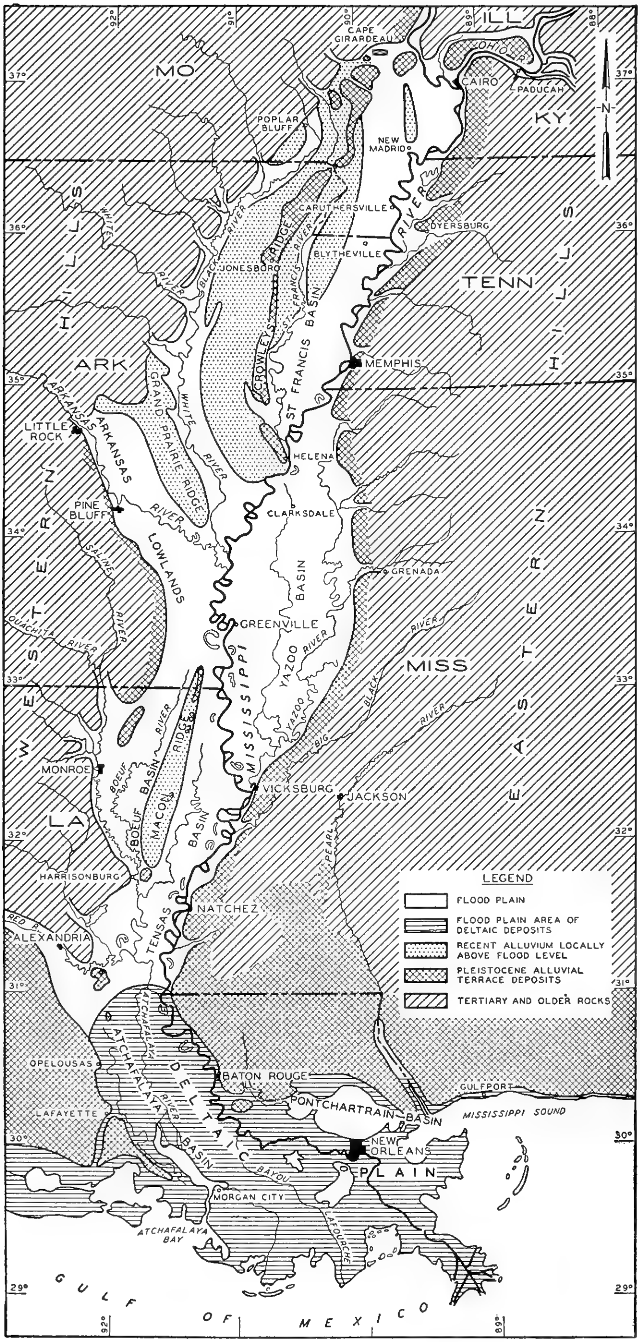

FIG. 1. Extent of flood plain and of adjacent deposits in Lower Mississippi Valley.

is rarely found. Also, going north anywhere beyond the Louisiana-Arkansas line, the gravels lie close to the surface, often within 15 feet; however, coming south into Louisiana and southern Mississippi, the cover thickness increases so that the gravels are 100 feet below the surface in the vicinity of Houma, Louisiana. Thicknesses within the graveliferous sections as a result of slope controls during deposition show somewhat less of a distinct north-south variation than is found in the overlying finer deposits. The gravel section near Sikeston, Missouri, is 180 feet in thickness. Near Memphis, Tennessee, the section is on the order of 100 feet but increases again to approximately 150 feet in the latitude of Yazoo City, Mississippi. Near Natchez, Mississippi, the value is about the same, but near New Orleans a thickening occurs in the deep-lying gravels so that 200-foot units can be measured. Also, there are important changes in the gravel sections within local portions of the valley, the gravels being thicker toward each tributary stream, where they assume a fan-shaped form.

The non-graveliferous deposits are themselves divisible into two phases:

(1) A pervious phase composed mostly of clean, well-washed sands exists in the lower part of the section. These thin out toward the north, where the whole section diminishes, and also thin southward because after alluviation became advanced sand was no longer carried in large quantities by the river below the central part of the valley.

(2) The upper, less pervious phase consists of a layer of silts and clays which thin to the north but thicken southward and become especially thick in southern Louisiana, where they are part of the deltaic mass. These are the most typical materials of the modern Mississippi River flood plain, and they are the most important in their effects on modern river behavior.

A special sort of sediment, the origin of which has been disputed in the Lower Mississippi Valley, is the loess that caps almost all terrace deposits along Crowley's Ridge and the eastern Alluvial Valley walls. It extends from north of Cairo, Illinois, all the way southward to Bayou Sara in Louisiana. The loess is a homogeneous, unstratified, calcareous silt with some plasticity and has a tendency to vertical cleavage. Its thickness on hill crests varies from as much as 65 feet near the Alluvial Valley bluffs to about 10 feet or less on terrace margins. There it merges into a similar soil material known as brown loam.

In Fig. 2 there is depicted a geological section through Recent and Pleistocene deposits of the Mississippi Valley in the latitude of

Natchez, Mississippi. The sedimentary sequence in both the valley fill and terrace deposits is indicated in the coarse to fine gradation of the materials in these sections. Loess is represented as restricted chiefly to crests of terrace hills of the eastern valley wall.

Meander-Belt Sediments

When sea level reached what is essentially its present stand, the Mississippi River ceased carrying coarse sediments into its valley and achieved what has been called a "poised" state. This is a condition in which the river has no pronounced tendency to do much valley deepening or filling. However, the behavior of the river is such that earlier sediments through which it flows become reworked to produce meander-belt deposits having distinctive properties.

In a poised river, meandering or the development of "bends" is a trademark. And, as these loops in the river's course are continuously enlarging and being abandoned while newer belts form, they result in reworked sediments that are left as superficial scars covering much of the flood plain. Resulting sediments of the following sorts are typical in the Mississippi River Valley (Fisk, 1947). Figure 3 depicts the various types of deposits.

Point-bar deposits. As meander loops increase in size, the core of land in their interior expands through the addition of a series of arcuate ridges and intervening swales, which result from river deposition in a strip-like manner on growing bars. Most of the sediment contributed consists of sand and coarse silt. Topographically, these ridges may average 6 to 10 feet in height and usually conform to the channel curvature within which they were formed. As a result of frequent downstream migrations of channels which accompany bar development, these strips often truncate each other and otherwise complicate their patterns. Such truncation of bar ridges and the relation of these ridges to each other as individual accretions are shown in the point-bar deposits pictured in Fig. 3.

Swale fillings. The swales, or topographic lows between accretion bars, often develop dense willow growths and trap fine sediments during high water long after their bordering ridges have developed. Thus these ridges become separated by intervening shallow strips of silts and silty clays which contain much organic matter. Within the point bar of Fig. 3 are swale strips situated between the bar ridges. The swales can be recognized by their heavy vegetation.

Natural levees. Natural levees are the higher parts of a river's flood plain, and they flank the immediate sides of its channel. These deposits are laid down in the form of thin layers resulting from deposi-

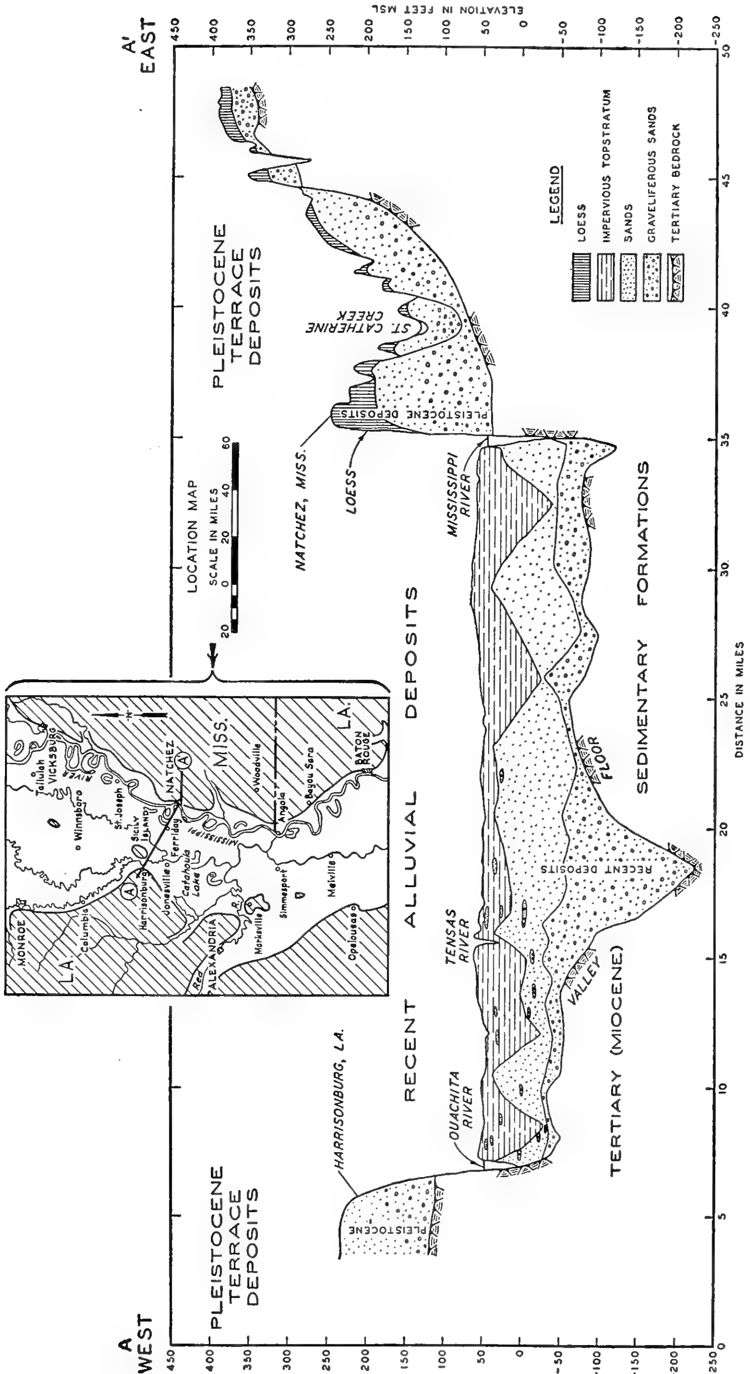

FIG. 2. Geological section through Recent and Pleistocene deposits near Natchez, Mississippi.

tion when the river overtops its banks during flood. The sudden loss of velocity, and consequent carrying power, of river water upon leaving its channel during flood results in deposition of thick, coarse silty materials nearest the river and successively finer grained and thinner deposits at a greater distance. The natural levees of the Mississippi River are approximately 10 feet in height, but near New Orleans and out onto the delta they are lower and extend to varying depths below the flood-plain surface, often more so below than above, as the load of these natural levee deposits has caused depression of soft underlying materials. Levee widths are extremely variable, from ¼ mile or so to as much as 4 miles. Normally they are widest behind concave banks and are also likely to widen downstream from a bend. Surrounding False River (Fig. 3), distinct natural levees can be distinguished by their utilization for agricultural purposes. These form the firm land in this area and have the added advantage of being slightly above normal flood level.

Crevasses. In areas directly behind natural levees there are frequent topographic irregularities caused by crevasses developed during floods. These features are almost like river distributaries, but they are smaller and much more temporary, serving only during very high water. Deposits laid down in this manner are generally thin but have many irregularities resulting from all sorts of braided-channel patterns. Silts of crevasse origin may form thin veneers over troublesome plastic clays and prove misleading in engineering work unless very careful borings are made. Scouring action by sudden crevassing sometimes produces limited basins known as "blue holes," which are filled with clays and fine silts after their channel has been abandoned. Crevasses are recognizable in the natural levee south of the point bar of Fig. 3. Here the channels can be seen to have developed small scour holes and to terminate with distributary courses. The crevasse channels in this area have become wooded, and their adjacent silty deposits have been utilized for farming.

Channel-fill deposits. With abandonment of meander loops by development of natural cutoffs, the familiar oxbow lakes are formed. These, however, are only temporary features, as tributary creeks and river floods tend to fill them slowly. In time these crescent-shaped scars become filled chiefly with fine clayey sediments, so that they have earned the name "clay plugs." Generally, in the basal part of a section, the clay is heavy and plastic. Above this, the material is more silty and less plastic, and, near the ends of the crescent, the material may be sandy or composed of coarse silts. The upper arm of a crescent generally accumulates the coarsest sediment, whereas the lower arm fills more slowly and with finer material. Maximum thicknesses of these plugs generally occur in the bendways where 75 feet or so of sediment is an average accumulation in old Mississippi River scars. False River of Fig. 3 is such an oxbow lake of an abandoned meander

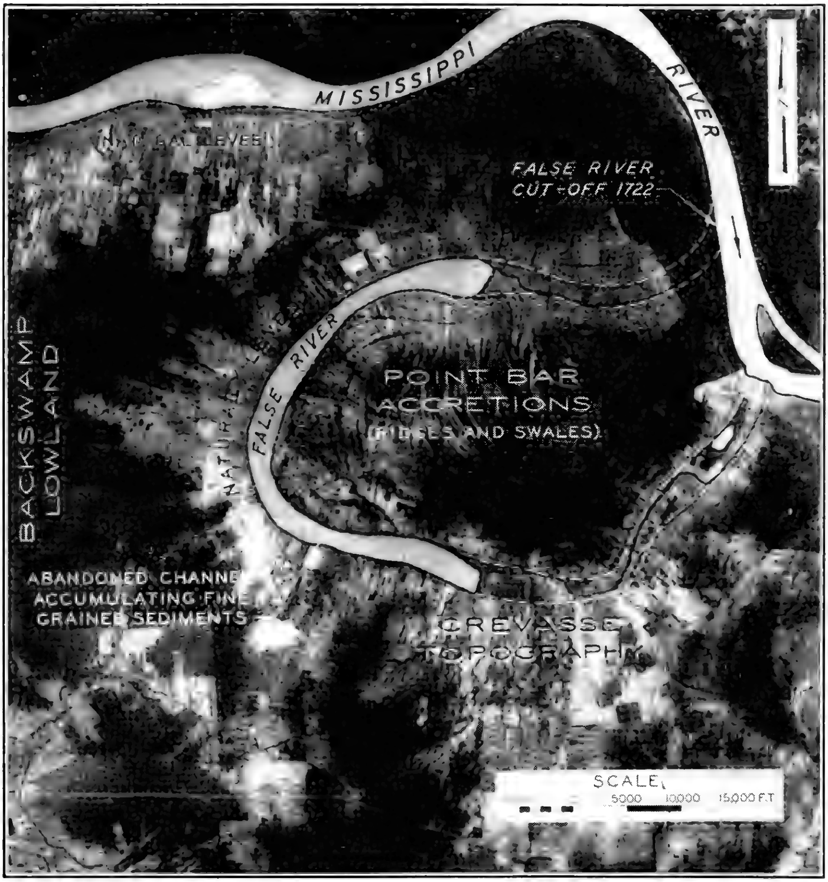

FIG. 3. Aerial view of typical meander-belt deposits and adjacent backswamp, False River, Louisiana.

loop and is at present slowly filling with fine-grained deposits. From the illustration it can be seen that the crescent points have already become filled and that sediment continues to be brought in by small tributary creeks.

Backswamps. Adjacent to the meander belts in the Lower Mississippi Valley are restricted low-lying areas known as backswamps, which receive considerable fine sediment during flood inundations.

The deposits are mainly very thinly laminated clays and silts which may contain organic matter, especially in southern portions of the valley. In addition, deltaic backswamp deposits contain much fresh organic material such as wood and roots of trees (Russell, 1933). The sediments are nearly always calcareous, as soluble materials tend to be concentrated in these basins. They vary in thickness from less than 20 feet in the latitude of Memphis to over 70 feet southward in Louisiana, where they merge into the deltaic deposits along an indistinct line. Adjacent to the natural levees of Fig. 3, backswamps can be recognized from their low-lying, wooded appearance and their lack of directional drainage.

Influences of Flood-Plain Deposits

The flood plain in the Lower Mississippi Valley covers approximately 35,000 square miles, a value slightly greater than the area of Louisiana. In addition there is a non-flood-plain portion of the Recent alluvium which consists of levels between the lowest terrace and the present flood plain. These surfaces are low fans which extend from valley entrances of tributary streams and are being dissected under present conditions. Areal extents of these fans are pictured in Fig. 1.

Within its flood plain, the Mississippi River has distinct regional variations of behavior which are related to the sediments through which it flows. Southward from Cairo, Illinois, the river flows in a region of coarse deposits where its channel is chiefly in sands and silts. Under these circumstances the river tends to develop wide, shallow channels and meanders extensively. Below Helena, Arkansas, sands and silts continue to predominate but with the influence of varied meander-belt deposits. Farther southward in the area of deep, fine-grained deltaic sediments, which are resistant to scouring action, channels tend to be narrower, deeper, and more stable.

In general, as a result of regional sediment changes, the Mississippi River may be designated according to the following behavior units:

Commerce, Missouri, to Helena, Arkansas. The river is broad and shallow and has many towheads and a high percentage of reaches. Channels shift rapidly.

Helena, Arkansas, to Angola, Louisiana. Here there are deeper, narrower channels with fewer reaches and fewer towheads, although meandering still takes place rapidly. In this region the channels are complicated through influences of excessively variegated meander-belt sediments.

Angola, Louisiana, to the gulf. The channel is deep and narrow but with much less meandering. False River, Louisiana, is the southernmost cutoff, and Thompson Creek, Louisiana, is the southernmost point at which gravels are dumped into the Mississippi River. Below Baton Rouge, Louisiana, meanders and point bars form very slowly, whereas south of Donaldsonville, Louisiana, the channel is almost stationary. Here the sediments are composed almost entirely of clay and fine silt which, owing to their cohesiveness, are extremely difficult for the river to erode. Meanders in the modern delta are almost non-existent, with the few bends present showing very little change from the earliest surveys to the most recent.

In meander-belt areas, the variety of sediments already discussed exert many material influences on river behavior where they are cut into by encroaching channels. The effects are generally directly related to grain size and plasticity of sediments and extent of individual deposits. The following basic subdivisions of the alluvial fill materials may be made.

Coarse-grained soils. SANDS AND GRAVELS. These materials wear away easily through the process of surface sloughing. Little resistance is offered to river migration, and channels are wider and shallower than those in finer grained soils.

Fine-grained soils. SILTS (semi-plastic to non-plastic). These soils are more cohesive than sand and offer more resistance to meandering. The river is restrained to some extent by finer, more cohesive silts, so that some banks become comparatively stable.

CLAYS. Of all the flood-plain sediments, clays offer the maximum resistance to river erosion. Banks tend to be quite stable, and channels cutting into such deposits tend to be narrow, as evidenced by the Mississippi River in the southern portion of the valley. Since clay plugs exist in considerable numbers in the upper reaches of the valley and are of considerable individual size, they are often of great importance in halting river migration at various points. Integration of levee systems with existing clay plugs may serve to increase the usefulness of the former.

The knowledge of relative stability of river channels as determined from adjacent sediments is of valuable assistance in engineering planning.

ENGINEERING PROBLEMS

DESCRIPTION OF ENGINEERING STRUCTURES

Vast areas of land in the Alluvial Valley of the Mississippi River would be inundated were it not for the levees along the river and along some of its tributaries. When it is realized that the Mississippi River is approximately 1,000 miles in length from Cairo to the gulf, and that levees lie on one or both sides of the river for the greater portion of this distance, it is apparent that the construction of levees is not only a major factor with respect to the economics and life of the large area within the Alluvial Valley but that also such a levee system presents some major engineering problems. Levees vary in height from relatively low structures up to heights rivaling many small earth dams, and levee heights in excess of 40 feet are not unknown.

In addition to levees along the main river, flood-control structures on the tributaries are also required. In order to prevent flooding of the Alluvial Valley by tributaries of the river joining it below Cairo, dams have been and are being built to provide storage areas and thereby control flood stages. These dams include Sardis, Arkabutla, Enid, and Grenada in Mississippi; Blakely Mountain and Narrows in Arkansas; Ferrells Bridge and Texarkana in Texas; and other dams in Arkansas, Louisiana, and Texas.

In order to provide for the requirements of navigation and local drainage, a large flood-control system must be supplemented by locks, floodgates, and miscellaneous drainage structures. All these structures are important to the proper integration of the overall system, and some present major design and construction problems, which will be discussed below.

Description of Soil Conditions

The discussion of the geological history of the Alluvial Valley has demonstrated that wide variations in soil types and states are to be expected as a result of sedimentation and fluvial action. These in turn give rise to radically different problems from the engineering viewpoint. The preponderance of sand in the northern portion of the Alluvial Valley indicates that, in general, the problems to be encountered will involve underseepage and through seepage in levees. However, even in this area, channel fillings, natural levee deposits, and other characteristic fine sediments deposited by the river give rise to the question of stability of the foundation and resistance to settlement.

In the central portion of the Alluvial Valley the deep beds of sand and gravel are overlain by clayey and silty soils. In addition, the Mississippi River in this portion of the valley has meandered extensively. Consequently, soil types and soil states are extremely variable and require an engineering and geological study to answer satisfactorily questions involved in the design of levees and structures, such as bearing capacity, settlement, seepage, etc.

In the southern portion of the Alluvial Valley the soils, from the surface down to a considerable depth, consist largely of clays and silty soils which in turn overlie deep beds of sand. The clay is highly plastic in some places. The Atterberg liquid limit generally is in excess of 50, and values greater than 100 are not uncommon. The natural water content of some of these fat clays ranges between 50 and 100 percent. It is evident therefore that primary engineering considerations in this region are stability and settlement.

The loess deposits found along the east wall of the Lower Mississippi Alluvial Valley are unique in their physical properties and present many unusual problems when utilized as a foundation or construction material. Their marked tendency to lose shear strength when subject to saturation or remolding and to erode easily when in an undisturbed state introduces many problems. However, when properly compacted, they possess good shear strength and are quite resistant to erosion. The great difference in strength and erosion resistance of loess which has been properly compacted and loess which has received inadequate compaction at water contents substantially above or below optimum is particularly striking. Loess was used in the embankment of Arkabutla Dam with entirely satisfactory results.

Levee Design and Construction

The wide variation in foundation soils and in borrow materials available gives rise to a multitude of problems. In the northern portion of the valley the sandy foundations are generally stable but are extremely pervious, and considerable underseepage that must be satisfactorily controlled may be present. In this region it is often difficult to find sufficient impervious material to cut off satisfactorily seepage through the levees, and to provide an impervious blanket on the riverside face. In addition, levees must often cross abandoned and filled stream channels, which filling may consist largely of fat clays and silts deposited in water and never exposed to any appreciable amount of drying or to any overburden load. In some cases these materials are not even consolidated under their own weight. Foundation stability becomes a major feature in these locations, requiring the taking of undisturbed samples that can be tested in the soils laboratory.

Problems involved in levee design and construction in the central portion of the valley are somewhat similar to those in the northern portion except that, because the top stratum in many places is thicker and the river has meandered more in the past, difficult foundation problems involving stability are of more frequent occurrence. It is of importance not only to determine the locations of abandoned stream channels by geological investigation but also to determine the physical properties of the materials, because the soils may be in a very weak state. For example, the shearing strength of clays as determined from unconfined compression tests may be as low as 0.2 ton per square foot or even less. Seepage beneath the levees is also of importance at many locations in the central portion of the valley, as in the northern portion, and a highly specialized technique has been developed for controlling sand boils which develop during flood stages of the river. Much engineering talent has been devoted to these techniques, which involve the proper method of bagging sand boils and the construction of sublevees, protection of caving banks, and other related problems. Fighting a flood brings as many and as difficult engineering problems as does the problem of design and construction of a levee system.

Since the soils in the southern portion of the valley are generally clays to considerable depths, levee design and construction problems in this region are more concerned with foundation stability than with underseepage, although there are some notable exceptions. In this region the required heights of levees are less than in the central and northern portions; this is fortunate because the strength of the foundation soil, in general, also is less. Shear strengths below 0.2 ton per square foot are by no means uncommon, and it is evident that foundation stability becomes almost an insuperable problem in some locations. These problems have been solved successfully in the past through determination of the properties of the soils by laboratory tests and the design of berms on both landside and riverside of the levee to give greater stability. In some cases construction has been prosecuted in stages which continue over intervals of years so as to bring the levee to grade gradually, thereby allowing the soils to consolidate and gain strength. Occasionally, levees have been built by the displacement method; that is, construction is continued in a normal manner and the weight of the embankment squeezes out the unstable material in the foundation. As much as 200 percent of the material composing the normal levee section has been required in some cases before stability was reached and the levee finished to grade.

Revetments

The meandering of the river frequently endangers the existence of the levees. In some instances this necessitates construction of a setback levee, but in places this cannot be accomplished, owing to the location of a town or to the relative economy of bank protection in place of levee construction. The design and construction of revetment involves construction, soils, and hydraulic problems. Before a revetment is constructed, the engineering problems involved concern the alignment of the river and related considerations. The revetment constitutes a protective coating laid on the bank to eliminate or reduce loss of material due to the river's attacking the bank. Revetments have been quite successful in this respect, but it is apparent that a revetment in itself has no structural strength and will be carried away if the bank on which it is laid is unstable. Thus, important engineering problems are involved in the determination of the stability of a bank when subject to scour and seepage forces. The determination of a safe slope to which the bank can be graded is important, for the cost of the work involved is greatly dependent on this slope. Construction problems increase greatly if the bank becomes flat, and slopes flatter than 1 on 3 or 1 on 3.5 are difficult to revet, from the construction viewpoint, and very expensive, from the economic viewpoint. Consequently, low factors of safety must often be used in determining a satisfactory slope to which the bank may be graded for placement of revetment. As a matter of interest, the Mississippi River Commission has under investigation at the Waterways Experiment Station a combined hydraulics and soils investigation of factors affecting the location, design, and construction of revetments. This includes an analysis of reasons for failures which may be due both to the large hydraulic forces involved and to the physical properties of the materials, such as shear strength, resistance to seepage forces, structure, density of sand deposits, and susceptibility to flow slides.

In the northern and central portions of the valley, revetments are important in protecting sandy river banks against scour. Seepage forces due to the natural draining of water out of the banks or to rapid fall in river stages become important, especially if the soils are not free-draining. Many drainage methods have been investigated by the Mississippi River Commission, and horizontal drain wells are now being considered.

In the central portion of the valley, banks often consist of a top stratum of silts and clays 20 to 40 feet thick overlying deep beds of highly pervious sands and gravels which are readily attacked by action of the river, whereas the top stratum is more resistant. However, the top stratum may have a low shearing strength; then the problem becomes complex, because the revetment must be laid on a bank, which must be graded to a slope that is stable, and must protect underlying sandy sediments which are easily scoured out.

In the southern portion of the Alluvial Valley the surface clays extend to such depth that protection of silty sediments against attack by the river becomes of less importance. As a result of the resistance of these clays to erosion, the tendency of the river to meander is much less than in the central and northern portions of the valley. However, a much greater concentration of industrial facilities along its banks has taken place; this in turn causes minor tendencies to meander and local stretches of bank instability to become major problems. Wave wash does become of considerable importance in revetments in this area, as is readily apparent, because ocean-going vessels regularly travel as far upstream as Baton Rouge.

Excavations

The making of excavations of any considerable depth in the Alluvial Valley presents varied engineering problems, as these excavations may be made in very permeable sands or in weak, fat clays of low shear strength. Furthermore the bottom of an excavation may be located in impervious clays that overlie highly pervious sands of depths that may exceed 100 feet and that connect directly with the Mississippi River. Thus wellpoint systems are often necessary in the northern and central portions of the valley to lower the ground-water level in the permeable sands and to prevent loss of stability of banks and foundations due to seepage forces. The high ground-water level usually found throughout the Alluvial Valley results in high heads which must be provided for. Excavation in clays where shear strengths may be less than 0.2 ton per square foot makes necessary an engineering study to determine the allowable slope to which the bank may be cut. Undisturbed samples of soil are regularly obtained and tested in the laboratory for large excavations. Slope analyses are made by the circular-arc method or the method of sliding wedges, depending on which method may be most applicable.

The presence of a pervious formation beneath the clay often makes it necessary to install wellpoints or deep wells to relieve uplift pressure against the bottom of the excavation, even though the excavation is in clay out of which a negligible amount of water flows into the excavated area. Since the sand and gravel formation beneath the surface in the Alluvial Valley is so highly pervious, even in the southern portion, and connects with the Mississippi River, the possibility of excessive uplift must be taken into account, even though the river may be many miles away. An example of such variation in head in the pervious sand and gravel formation in the southern portion of the valley near Baton Rouge is shown on Fig. 4, which shows the level in piezometers corresponding to variations in stage in the Mississippi River, which at this point is 10 miles away. The effect of these uplift pressures must be considered in planning the excavation, and methods must often be provided for their control and observation during con-

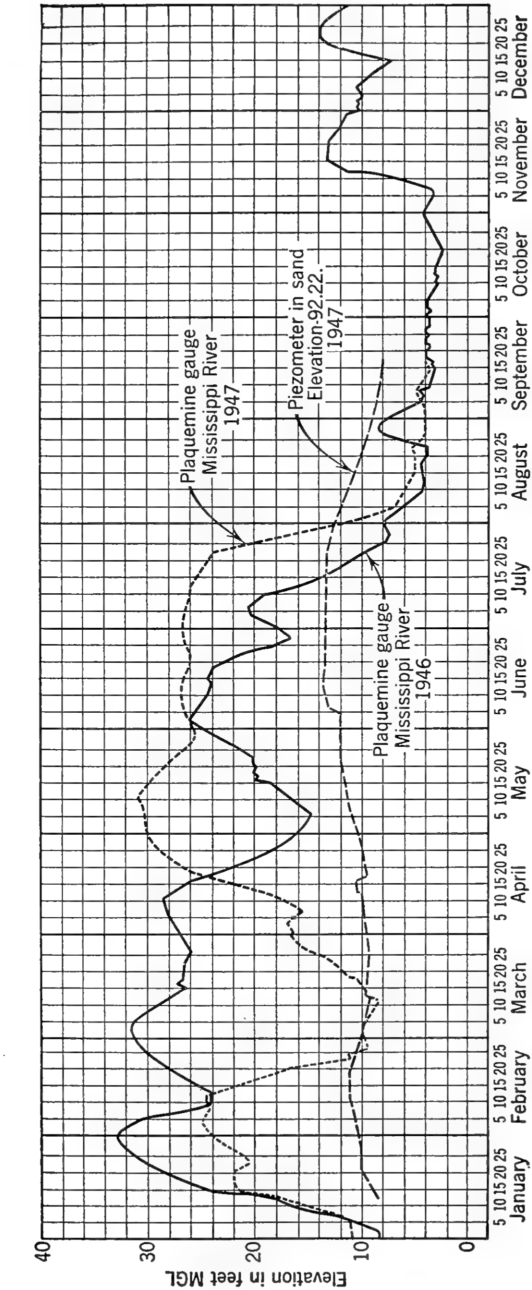

Fig. 4. Hydrograph of Mississippi River and deep piezometer readings.

struction. A particularly interesting case which involved the combination of excavation in very weak clays underlain by sand stratum is afforded by the construction of the Algiers Lock across the river from New Orleans, which is now under construction by the New Orleans District, CE. This situation was further complicated by the fact that gas was present in the sand stratum, and it was necessary that the gas pressure be relieved. The New Orleans District accomplished this by installation of pressure-relief wells which permitted the gas and excess hydrostatic pressures to be dissipated.

Structures

The many floodgates, locks, and other drainage structures which are required give rise to many foundation problems which require geological and engineering studies for the economical and successful solution of design features. The geological study often results in relocation of the structure to avoid recent channel fillings and other undesirable foundation conditions. The engineering study is concerned with obtaining undisturbed samples of soil where required, testing samples in the laboratory, and evaluating such questions as allowable bearing capacity if spread footing is used, or the length of piles necessary if a pile foundation is required, estimate of settlement of the structure, and provisions for handling seepage beneath the structure, which often acquires considerable importance. Problems involved in making excavations for structures have been described in the preceding section.

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Part 3

APPLICATIONS OF PROCESSES OF SEDIMENTATION

Chapter 13

RELATION OF LANDSLIDES TO SEDIMENTARY FEATURES *

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Landslides have been the subject of considerable study for many years, and in many different countries, not only because they are of practical economic importance, but also because they are widespread, effective, and interesting agents in the shaping of land forms. There is now available a vast volume of observations by construction engineers, geologists, and interested laymen covering the many diverse phases of landslides and other kinds of earth movement. Most striking is the growing literature on the application of soil mechanics to the stability analysis of certain types of landslides. The subject of landslides now has many aspects that cannot be covered in a short chapter. The discussion to follow, therefore, will be principally a description of those features of sedimentary deposits which are recognized as contributing to true landslides, or which must be considered in their prevention, analysis, or cure. Some of the features described are not limited to sedimentary deposits; likewise many of the dynamic processes operate as well in metamorphic or igneous terrains.

To acquaint the reader with the terminology to be used, and with the typical form of the several kinds of landslides, C. F. S. Sharpe's classification and one of his illustrations, taken from *Landslides and Related Phenomena* (1938), are reproduced in Figs. 1 and 2. Readers familiar with this excellent work will recognize that much of what follows is an enlargement on his "active" and "passive" causes as applied to sedimentary deposits.

For the present purpose, the role of the major factors of (1) physical and chemical composition, (2) structure of the deposit, and (3) state of stress in the material in the production of some of the types of slides illustrated in Fig. 2 will be shown.

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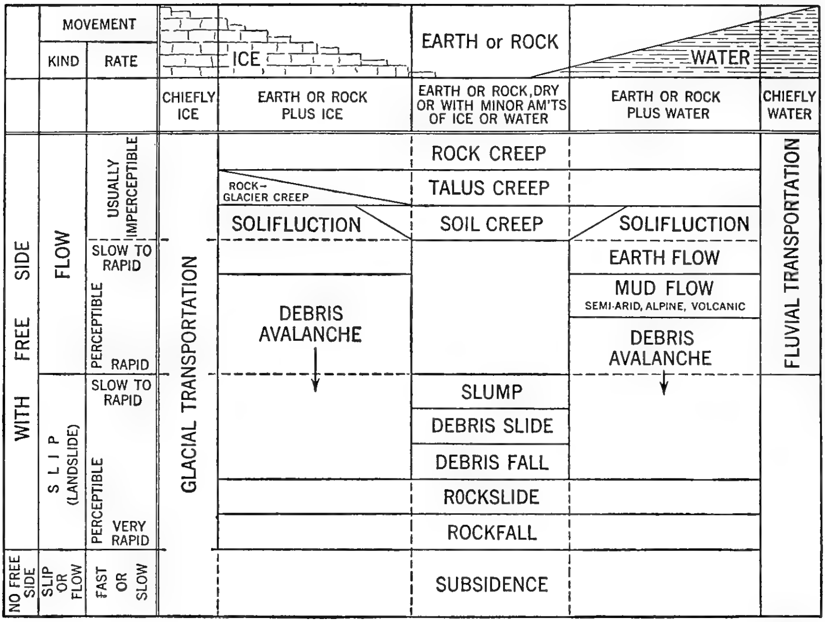

Fig. 1. Classification of landslides and related phenomena. (After Sharpe, 1938, by permission of the author and Columbia University Press.)

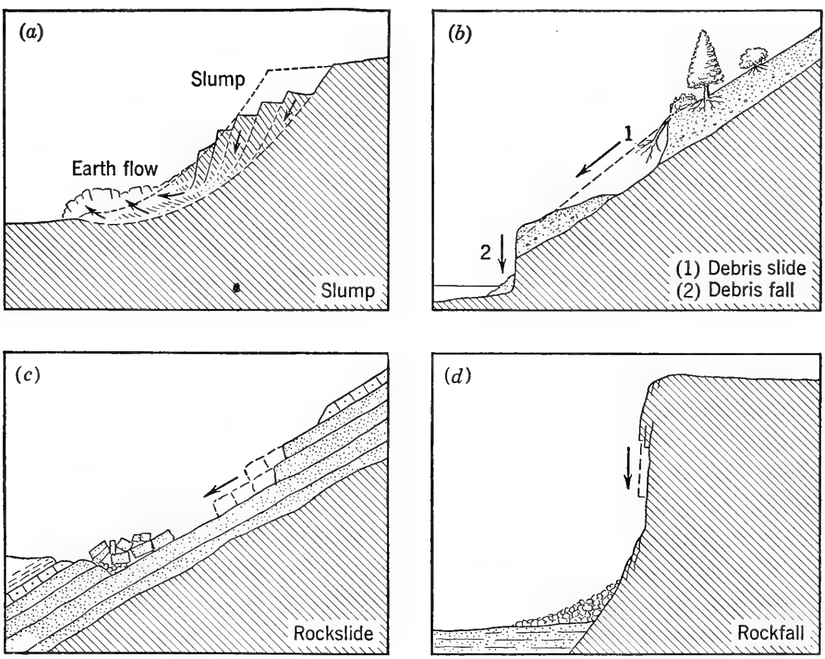

Fig. 2. The five classes of landslides. (After Sharpe, 1938, by permission of the author and Columbia University Press.)

MAJOR FACTORS

The major factors of composition, structure, and state of stress determine the equilibrium of an earth mass; the first two factors operate indirectly, and the last directly. These factors set the stage for sliding, and any change in one may itself disturb equilibrium or produce changes in other factors to lead to instability. For instance, a change in composition, such as increased water content, may change both the internal structure and the state of stress and lead to sliding. The variables comprising or influencing the major factors are commonly so interrelated that a discussion of their separate effects is impractical; therefore, they will be only briefly listed separately and their joint effects considered in more detail, with a number of examples.

Composition

Any sedimentary deposit consists generally of three phases, solid, liquid, and gas. Important factors in the physical composition of the solid phase are the size, size distribution, shape, area, and nature of surface of the individual rock or mineral particles; the amount and kind of cement; and the mechanical strength of the particles and the cement. Some of these characteristics may be permanent, some are variable. To be considered in the chemical character of the solid phase are mineralogy, chemical stability, and surface effects such as hydration and base exchange.

The relative abundance of the liquid phase is critical in determining the mechanical stability of fine-grained sedimentary deposits. The liquid, of course, is water. Many of the physical properties of sediments are determined by the peculiar properties of water and the state in which it is held; that is, whether or not it has a free surface, or is held in capillaries, or bound into a semi-solid state around the mineral grains, or actually enters into the crystal lattice of certain clay minerals. Air or other gases within an unconsolidated deposit may affect its physical and chemical properties.

Structure

For convenience, structure may be classed as either gross or fine. Gross structure includes stratigraphic sequence, attitude, homogeneity, and discontinuities such as bedding planes, joints, and faults. Fine structure includes the arrangement of individual particles into loose or compact structures, resulting from modes of disposition, or the interaction of surface forces of the solid and liquid phases.

State of Stress

The state of stress determines directly whether or not an earth mass is stable. Gravity is, of course, the prime mover and is occasionally aided by other forces arising within the material. The state of stress is determined largely by topographic form, but is also influenced by changes in composition and structure as they affect the distribution of stress among the solid particles, the interstitial water, and entrapped air.

OPERATION OF MAJOR FACTORS

Texture

The physical and physicochemical characteristics of sedimentary material and the relative abundance of water are of prime importance in the determination of stability.

The size of individual particles in a sedimentary deposit in itself does not greatly affect its stability, unless the size is of fine sand or smaller, where capillary forces, surface effects, or the peculiar hydration properties of clay minerals come into play. The effect of size in uniform conglomerate, gravel, coarse sandstone, and sand is primarily to produce high transmissibility, allowing water to migrate readily—possibly to adjacent shales where it may do real damage. The Telluride (San Miguel) conglomerate is believed by Cross (1899) to have so contributed to large landslides in the San Juan Mountains of Colorado. Coarse gravels capping shale mesas have been instrumental in guiding irrigation waters to slides along Cedar Creek, near Montrose, Colorado (Varnes, 1949). In even-grained deposits the permeability increases as the size increases (Fraser, 1935).

In graded deposits, the filling of voids with fine material affects the permeability and may affect other physical properties of the sediment. In dry cohesionless sands, size distribution apparently has little effect on compressibility (Chen, 1948), but in a cohesive clay soil, addition of gravel has been found to decrease compressibility (Murdock, 1948).

The shape of the constituent particles also influences the physical properties of soils and sedimentary deposits. In dry material, both the compressibility and the angle of internal friction (and hence shearing resistance) increase with increasing angularity of the constituent grains (Chen, 1948). The shape of the particles also influences the fine structure developed during the process of sedimentation and consolidation, and thus affects the density and shearing strength of the material. Laboratory tests show that, for sands of high roundness and sphericity, the density and porosity are quite sensitive to the rate of deposition (Kolbuszewski, 1948), slow deposition producing the denser deposits. The shape of mineral particles may also affect stability through preferred orientation. The writer has seen numerous rockslides along bedding planes in dipping sandstone near Glenwood Springs, Colorado. The bedding planes along which slippage occurred were covered with mica flakes lying in the plane of the bedding.

MINERAL CONTENT

Glauconite, a fairly common mineral in sedimentary rocks, may contribute to landsliding. An interesting example of a slide due to glauconite in the cliffs around Algiers Bay was described by Proix-Noé (1946) and by Drouhin, Gautier, and Dervieux (1948). The cliffs around the bay are composed of glauconitic marl underlying sandy limestone. Water percolating down through the limestone became charged with calcium carbonate. As the water entered the marl and contacted the glauconite, the calcium ions were fixed and potassium ions liberated The water became markedly more alkaline (*p*H 9), resulting in the deflocculation of the marl and the hydrolyzation of alumino-silicates. The marl was made highly fluid and could no longer support the overlying beds, so the cliffs collapsed. Glauconitic mudstones and greensands have been involved in landslides in New Zealand (Benson, 1946) and along the seacoast of England near Folkestone (Toms, 1948) although no reference was made in either description to possible physicochemical action of the glauconite itself.

Gypsum also may contribute to landsliding. It is moderately soluble, and its removal by circulating waters within a series of sedimentary strata may cause subsidence, or sliding if a steep face is exposed. It also has two other effects of quite different natures. The dissolving of gypsum disseminated through a shale, and its subsequent recrystallization along minute fractures close to the ground surface, are potent factors in breaking up and rendering permeable an otherwise rather massive and impermeable clay or shale. This process has destroyed effectively a grout surfacing placed on Mancos shale slopes at Mesa Verde National Park to prevent the shales from being wetted by rain. At that place, water could get at the shale behind the roadcut from an overlying permeable and fractured sandstone (Varnes, 1949). Even in flat ground, the crystallization of gypsum may cause sufficient swelling to damage structures (Joly and Ninck, 1935). Gypsum or, more properly, the calcium ion also contributed to landsliding in clays along the banks of the Volga River (Tchourinov, 1945).

This reference to base exchange in clay leads to the subject of the clay mineral group, which as a factor in composition ranks in importance with water in the determination of stability or instability of slopes. Clayey soils and sedimentary deposits are widely used as foundation and construction materials; they are involved in landslides throughout the world, and they pose problems of maintenance in countless railroad and highway cuts. The needs of engineering, economic geology, ceramic technology, and many other fields have resulted in intensive research on the physics and chemistry of clays, but only the briefest mention of a few of the results of this research can be made here.

For further information on clays, the reader's attention is directed to the many papers and their bibliographies in the First and Second International Conferences on Soil Mechanics and Foundation Engineering (at Harvard in 1936, and at Rotterdam in 1948); to papers in *Soil Science of America;* to texts on soil mechanics such as those by Terzaghi (1943) and Terzaghi and Peck (1948); and to articles by Grim (1942), Casagrande (1932), Terzaghi (1941), Hendricks (1942), Rutledge (1944), and Winterkorn (1942).

Physical Properties

The physical properties of earth materials that contain fine-size fractions depend very largely on the character of the smallest-size particles, especially those particles of less than 2 microns. The properties of these small particles are influenced by the intensity of the negative electric charge on their surface. Because water molecules are polar, the positive (hydrogen) ends of the water molecules are attracted to the solid particles, where they orient into an adsorbed layer. Near the mineral particle, the film is practically solid, farther away the film is viscous, and near the outer surface the water is liquid. If little water is present, the rigid, adsorbed layer on one particle meets that on another, and the whole mass is rigid or highly cohesive. With more water, the films thicken and lubricate the particles, making the mass plastic. With still more water the mass becomes fluid. The thickness of the water films, their degree of orientation, and their efficiency as binding or lubricating agents depend on the amount of water available, the charge on the mineral surface, and the surface area available among the mineral fragments. The clay minerals proper, through their habit of cleaving into minute flakes, present tremendous surface area. Moreover the arrangement of molecules on the crystal surfaces of certain clay minerals is favorable to the adsorption of water or to the adsorption of certain ions which themselves may attract thick water films. Montmorillonitic clays in which the exchangeable ion is Na^+ adsorb thick oriented films; they require somewhat more water to become plastic, and 5 or 6 times as much water to become liquid as do clays carrying exchangeable Ca^{++} or H^+. Thus they remain plastic over a considerable range of water content. Some clays also adsorb organic molecules and form gels in suitable organic liquids. Electron-microscope photographs show that clay particles tend to cluster around bacteria and bits of organic matter (see Jackson, Mackie, and Pennington, 1946, and its bibliography).

WATER CONTENT

In fine-grain sedimentary deposits, the water films around clay particles profoundly influence the forces holding the particles together, and also influence the arrangement of both the clay size and larger particles into structures that affect the porosity, shear strength, consolidation properties, and permeability of the deposit. All these factors in turn depend ultimately on the amount, kind, and size distribution of the clay and non-clay size fractions, the kind and concentration of exchangeable ions and soluble salts, the type and amount of organic material present, the mechanics of deposition, the past loading history of the deposit, and the past history of wetting and drying cycles.

Tchourinov (1945) has explained the slides in Cretaceous clays along the banks of the Volga River somewhat as follows. During the process of weathering, pyrite in the clay decomposed, calcium carbonate in the clay was attacked, magnesium ions increased through the decomposition of glauconite, and the ratio of sodium to calcium and magnesium in the clay decreased markedly. Presumably through base exchange involving the calcium or magnesium ions or both, the thickness of bound-water films decreased, and the clay assumed a granular structure leading to increased porosity, permeability, and free water content. Cohesion and shearing strength decreased and sliding occurred. Only the weathered clay was involved in movement.

When unfissured natural earth materials are mechanically mixed and remolded at constant water content or even disturbed by vibration, they commonly lose much of their shear strength. In clayey materials the mechanics of the change is imperfectly understood, but it is thought that loss of strength is due to a breaking down of more or less loose structures in which the larger particles are cemented together or supported by the fine clay-water particles, or by the shearing off of the water films which bind the clay particles together. Upon resting, even at the previous water content, disturbed clays may regain a considerable portion of their strength, probably through the reconstruction of the water films (Moretto, 1948).

This sensitivity of fine-grained deposits to disturbance makes difficult the control of those slides in which slump blocks turn rapidly into semi-liquid earth flows as the material becomes disturbed (see Fig. 2*a*).

VIBRATIONS

Earth flows may be initiated by vibration. In describing earth flows that accompanied the San Francisco earthquake, Anderson (1908) says, "In certain cases the water seems to have risen with a gush, as if actually squeezed from the hills." The author suspects that the vibrations caused the natural structure of the soil to break down and the soil to consolidate. Some of the water held tightly in small voids and bound around the mineral particles was freed, and it locally oversaturated the soil to cause flowage.

A landslide along the banks of the Gerzenzee in Switzerland (von Moos and Rutsch, 1944) was due to the breaking up of the structure of a marl bed by the felling of trees and blasting of stumps. Here the marl bed beneath a cover of peat had remained stable, even though it was highly saturated, because of a gel structure involving organic material. When disturbed, the mass liquefied and flowed out into the lake, and the shore subsided.

Fine-grained deposits of clay or silt size, but consisting of relatively fresh rock flour rather than clay minerals, are particularly susceptible to disturbance. Such deposits are common in lakes that have received glacial detritus and include varved "clays." The water content of this material in its natural state commonly equals or exceeds its liquid limit, and although it may be trimmed back to stable slopes, it has little cohesion and cannot be handled without loss of strength (Legget and Peckover, 1948; Tschebotarioff and Bayliss, 1948).

Fine sand, if it is saturated and below its maximum density, may flow readily if support is removed. Peck and Kaun (1948) describe the liquefaction of sand deposited by a dredge behind sheet piling when two of the sheet piles were removed. Progressive flow slides in the Dutch province of Zeeland in sands below the critical density exposed to tidal scour have been described (Koppejan, Van Wamelen, and Weinberg, 1948).

GROSS STRUCTURE

Clay minerology and the structure of fine-grained materials play a prominent role in the stability of poorly consolidated materials, but the previous discussion may have overemphasized these particular points because of the interesting advances in current research.

Homogeneous deposits of clay or silt are uncommon, and it is generally necessary to take into account many other factors that bear on the arrangement and grosser structures of the deposit before a rational approach to analysis and cure of a slide can be made. In particular, the stratigraphic sequence, the attitude of the strata, and the presence of discontinuities such as joints, faults, and bedding planes exercise their own kind of control. The influence of these large-scale structures is generally apparent after short study of any particular slide. Their action is well-known and has been often described; hence it will not be greatly detailed below.

Flat-lying stratigraphic series in which massive beds are interstratified with or underlain by shales or clays and exposed by erosion into steep slopes are commonly subject to landslides if the shales are wetted. Climate and the stratigraphic sequence of alternating massive sandstones and limestones with shales have produced erosion forms particularly susceptible to landslides in the Colorado Plateau (Hinds, 1938; Reiche, 1937; Strahler, 1940; Varnes, 1949). Massive volcanics interbedded with or overlying shales have been involved in many slides in the canyons of Idaho (Russell, 1901) and in the San Juan Mountains of Colorado (Cross, 1899; Cross and Spencer, 1900; Howe, 1909).

PERMEABILITY

Permeable beds or lenses within fine-grained deposits are especially dangerous, for they allow water to reach and lubricate large surfaces. A slide in interbedded shale and sandstone at Soldier Summit, Utah, in a cut of the Denver and Rio Grande Western Railroad was probably aided by water from an underlying porous sandstone. Owing to dip and impermeable cover, the water in the sandstone bed was under considerable pressure at the site of the slide. If the permeable beds are also loose, the danger of internal erosion and loss of support is added to the possibility of failure by rotational shear slip. An interesting example of the influence of a permeable sand bed on a landslip on the south coast of England is described by Ward (1945, 1948).

INCLINED STRATA

If the strata have a component of dip toward the free face of a valley wall, the tendency for slippage along incompetent strata is, of course, greatly increased. A large rockslide of this type occurred in the Gros Ventre River valley in Wyoming in 1925 (Alden, 1928). Slippage took place obliquely down dip along clay beds in a series of sandstones and limestones. The slide mass dammed the river and formed a large lake. Two years later the dam washed out, causing a disastrous flood downstream.

FRACTURES

Joints and fissures of various kinds not only weaken any mass of earth material, be it solid rock or clay, but also allow water to enter. The properties of stiff, fissured clays are quite different from homogeneous intact clays. Stiff, fissured clays are usually very compact, but they contain innumerable fractures that run through the mass. The common characteristic of stiff, fissured clays is that if a lump of such clay, with a moisture content below the plastic limit, is dropped, it breaks into polyhedric fragments with dull or shiny surfaces that may differ in color from the mass (Cassel, 1948; Terzaghi, 1936). Clays of this type have been consolidated under considerably higher pressure than their present surcharge and have been lifted and exposed by erosion. Whereas the vertical pressure has been reduced, the horizontal pressure, corresponding to the previous high vertical stress, remains in considerable part. The fissuring is believed to result from the differential variation of the vertical and horizontal pressures during the geologic history of the clay and from the ensuing shear stresses. As soon as the horizontal resistance is decreased through excavation, the clay expands and the fissures open. If water enters the fissures, a progressive softening occurs, gradually reducing the strength of the clay mass. The rate of softening depends on many factors. Skempton (1948) describes slips in London clay that occurred from 5 to 40 years after the cuts were made.

Landslides in hard rock commonly occur along, or are at least in part controlled by, joint surfaces. Many such slides, generally of the rockslide or rockfall type, have been recorded. A notable example is the Turtle Mountain slide at Frank, Alberta, in which approximately 41,000,000 cubic yards of limestone, weakened by joints across the beds, descended into the valley, just touched the outskirts of the town of Frank, and killed 70 people (Daly, Miller, and Rice, 1912).

Faults may exercise control similar to joints, with the added factor of possible clayey gouge or loose breccia along the fault surface to aid movement. Wide fault zones, in which the material is highly brecciated, are always potential sources of trouble in deep excavations of any kind. Even geologic contacts between different types of rocks may act as sliding surfaces. Sharp (1931) describes a large slide in Wyoming in which Tertiary sand and gravel apparently slid along the sloping contact with underlying crystalline pre-Cambrian rocks.

In short, the effect of discontinuities of any kind must be evaluated in the analysis of the stability of slopes. This is especially true if the fractures are so disposed as to create an unfavorable distribution of stress within the deposit.

Stress Distribution

Some general remarks on the distribution of stress within earth materials are perhaps in order. In determining the factor of safety of a slope, one must compare two sets of forces: those that tend to produce failure and those that tend to prevent it. The force of gravity is certainly the prime source of stress tending to produce failure, though it may be aided by forces arising from frost action or from the hydration of such minerals as gypsum or the clays. Gravity is a force that affects failure because internal friction on any surface within the mass depends on the effective normal stress on that surface. The resistance to sliding on any arbitrary surface in general consists of two parts, cohesion and friction, and is given by the well-known Coulomb formula:

$$s = c + p \tan \phi$$

The meanings of c, p, and ϕ vary somewhat with the material involved and the loading conditions. In clay and uncemented sands, the cohesion c is zero; p is the normal pressure due to the weight of overlying material; and ϕ, the angle of internal friction, is about the same as the angle of repose of the sand. If the sand is cemented, it is regarded as having a kind of cohesion. If it is moist, the sand has an apparent cohesion due to capillary tension of the moisture films between the grains. This vanishes if the sand is immersed. In addition, if the sand is immersed, the effective normal stress is equal to the total normal stress lessened by the buoyant effect of the water on the overlying material and by the neutral stress or pore-water pressure. If the pore water is in motion, seepage pressures must also be considered.

The shear strength of saturated sands depends on many factors; among the most important are the original state of aggregation or denseness of the deposit and the ability of water to migrate as stress is applied. If the density of the material is so low that shear stresses from additional loading tend to decrease the volume of the material, and if the load is applied so fast that the water content cannot change, part or most of the vertical load is transferred to the water, the effective intergrain pressure and friction are lowered, and failure may result. If the sand is dense, the volume will increase on shearing and the effective intergranular pressure will remain. Recent work by Geuze (1948) and others indicates that, if the original void ratio of a sand is above a critical value characteristic of that deposit, the sand will compact on shearing and, if drainage is not immediate, high pore-water pressures can develop.

Clays consolidate slowly, and the difference between shear strengths of saturated clays determined experimentally by quick or slow tests is frequently quite large. Some of the difference is due to the building up of pore pressures in the quick test, but the problem is still complex and subject to much current research. It has been found that, for soft clays, a satisfactory approximation to the shear strength of the material in place is given by:

$$s = \tfrac{1}{2} \text{ unconfined compression strength}$$

The presence of gas bubbles within a fine-grained deposit decreases its permeability somewhat and, hence, the rate of drainage, but it accelerates the rate of consolidation. Also, if clay contains air, the shearing strength derived from a quick test increases with increasing normal stress (Terzaghi and Peck, 1948, p. 89).

It is not the intention of the author to go further into the soil mechanics of slopes than is necessary to indicate that the distribution of stress among the three phases of a natural deposit is critical to the stability of a slope. From the above discussion it is apparent that shear strength of earth materials is a complex function of the relative density of the deposit, its water content, its permeability, and the strength of the individual particles. For natural sands, the relative density depends largely on the conditions and rate at which it was deposited; the relative density of clays depends chiefly on the loads that the soils have carried and, in some instances, the rate at which the loads were applied.

The permeability of a deposit is, of course, a function of many variables of the material, including particle size, size distribution, mineralogy, and structure. The development of pore pressures and the rate of consolidation depend in large degree on the permeability.

Pore-water pressure has been studied principally in regard to the stability of earth dams. Several failures of earth dams, notably those of the Alexander Dam in Hawaii (Anonymous, 1930) and the Belle Fourche Dam (Anonymous, 1933) have been ascribed to the development of excess pore-water pressures through lack of drainage. Pore pressures developed in the walls of cuts or natural slopes sometimes produce very rapid and disastrous slides. Stratified deposits consisting of layers of sand and clay and masses of cohesive soil that contain irregular lenses or pockets of sand and silt are particularly susceptible (Terzaghi and Peck, 1948, p. 365). Glacial and glacial-outwash deposits are commonly of this type. Beds or pockets of sand or silt become saturated during wet weather and may develop high pore-water pressure. These beds have little or no cohesion, and their shear strength is determined by (Terzaghi and Peck, 1948, p. 367)

$$s = (p - U_w) \tan \phi$$

As the pore-water pressure U_w increases, the shear strength decreases until the porous bed can no longer support the overlying mass. Failure takes place by outward spreading and breaking up of the overlying material on the underlying viscous bed. Such a failure by spreading may occur within a few minutes, in contrast to the slower action of slump in homogeneous clay.

It is hardly necessary to comment on the natural agencies of erosion and the work of man in the production of slopes that may become unstable. It should perhaps be emphasized that the stability of a given slope is not a constant for all time. As erosion proceeds, as the ground-water conditions fluctuate, and as changes in the state of hydration and structure of clays occur with the passage of time, the state of stress throughout the slope may change greatly. The original slope design must take these possibilities into consideration.

One must also consider the possibility of transitory stresses that arise from vibrations, blasting, earthquakes, or earth tides, triggering the failure of an otherwise stable slope.

METHODS OF COMBATING SLIDES

The methods employed in combating slides are generally curative rather than preventive. They depend on the kind of material, the area involved, and the type and rate of movement. These factors vary so greatly from slide to slide that the details of remedial measures are tailored to fit each slide.

The design of high embankments and cuts, or the combating of large and serious slides, generally requires geologic mapping of both the surface and underground, the studies of ground-water levels and pressures, taking and testing of enough samples to be representative, and the analysis of the stability of the deposit.

The purpose of a stability analysis is to aid in the design of safe slopes, to aid in the redesign of slopes that have failed, or to approximate the original physical properties of material that has failed along a known surface. Assumptions are necessarily made regarding the gross and fine structure of the deposit and the shape of the sliding surfaces. The dangers of these assumptions are well recognized, but, in many instances, at least an approximate idea of the safety factor is obtained. It is generally assumed that sliding occurs along the arc of a cylinder whose axis is parallel to the slope surface, and that the sliding block rotates about the center of the arc. The factor of safety is then defined as the ratio of the moments about the center of the arc tending to produce movement and tending to resist movement (Terzaghi and Peck, 1948, p. 184):

$$\text{Safetv factor} = \frac{\text{moment of resisting forces}}{\text{moment of driving forces}}$$

Various refinements may be made, such as the assumption that the surface of sliding is composed of a series of arcs of different radii. Many variables enter into the computation of the moments of the resisting and driving forces, and into the selection of centers and radii of the arcs. The factor of safety is computed for several surfaces, and that having the lowest factor is the one along which sliding may most probably occur. Such analysis is most successful if the material is homogeneous and if data on the strength of the material and subsurface stresses are ample.

Remedial measures for the cure of slides are generally aimed at changing one or more of the factors of composition, structure, or state of stress to restore equilibrium. Where slump or earth flow is involved, remedial measures include, if possible, changing the composition of the material by removal or diversion of water. Methods of removal include open or rubble-filled trenches, drainage tunnels, wells, reverse filters, drying by heated air, and electro-osmosis. Methods used to prevent access include surface diversions, grouting openings, sodding, and oiling.

Methods involving change of structure as well as composition, such as the introduction of gelling substances and stabilization by electric current, have been used in the stabilization of foundations, but the author is not familiar with their use in stabilizing slopes.

Methods of changing stress distribution include drainage to relieve pore-water pressure, cutting back slopes and loading the toe of the slide to decrease the moment of forces tending to produce sliding, and the use of various types of barriers such as retaining walls, cribbing, and piles. Small rockslides in dipping strata have been successfully stopped by blocking or pinning loose slabs to the underlying firm rock (Laurence, 1948).

Much has been written about the remedial measures applicable to landslides. The reader is referred especially to the works of Ladd (1935), Hennes (1936), and Forbes (1946); to the Proceedings of the First and Second International Conferences on Soil Mechanics and Foundation Engineering; to papers that appear occasionally in the *Proceedings* and *Transactions of the American Society of Civil Engineers;* and to many short articles in *Engineering News-Record.*

FUTURE RESEARCH

The cure for landslides is frequently difficult and costly, and all too often not completely satisfactory. Research in the problem of landsliding should be directed not only at devising new and better methods of alleviating slides, but also increasingly toward developing criteria for the recognition of potentially unstable areas. Much has been done along this line in soil mechanics, especially in the criteria of stability for more or less homogeneous clay. Much remains yet to be done in the study of the natural fine structures of clays and silts, how they develop, how and why they change with time, loading, and water content, and the role of mineralogy and soluble salts on changes in structure.

It has become increasingly clear that the stability of earth materials is a function of many factors, some of which are not easily recognized or evaluated. If the rank and file of engineers and geologists can become aware of the necessity for closer study of the slides they encounter, and if soil engineers continue their researches at the present pace, perhaps sufficient data will become available to permit formulation of general principles of slope stability, even for non-uniform materials.

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Chapter 14

PERMAFROST *

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Permafrost (perennially frozen ground) is a widespread geologic phenomenon whose importance and ramifications are rapidly becoming better known and more clearly understood. The problem is to understand permafrost in order to evaluate it in the light of any particular endeavor, whether practical or academic. To understand permafrost we need a precise, standardized terminology, a comprehensive classification of forms, a systemization of available data, and coordination of effort by geologists, engineers, physicists, botanists, climatologists, and other scientists in broad research programs. These objectives are only gradually being realized.

This chapter is largely a compilation of or reference to available literature. Its purpose is to acquaint geologists, engineers, and other scientists with some of the many ramifications and practical applications of permafrost. New data from unpublished manuscripts in the files of the U. S. Geological Survey also are included where appropriate for clarity or completeness. Inna V. Poiré of the U. S. Geological Survey has prepared numerous condensations of Russian papers on permafrost and made them available to the author. Others were made available through the National Military Establishment. The library of the Engineers School, the Engineer Center, Fort Belvoir, Virginia, has many abstracts, condensations, and translations of Russian works that are available to civilian readers. References in this chapter generally are only to later works, as most contain accounts of the earlier literature. The bulk of the literature, unfortunately, is in Russian and unavailable to the average reader, but some of it has been summarized by Muller (1945). The Arctic Institute of North Amer-

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ica (Tremayne, 1948) is currently making an annotated bibliography of all arctic literature, including permafrost. A list of 190 titles of Russian articles dealing with permafrost is given by Weinberg (1940).

The multitude of problems associated with frost action, as we refer to it in the United States, appropriately should accompany any discussion of permafrost. However, limitation on space permits only a passing reference to the relationship of permafrost to frost action. An annotated bibliography on frost action has been prepared by the Highway Research Board (1948).

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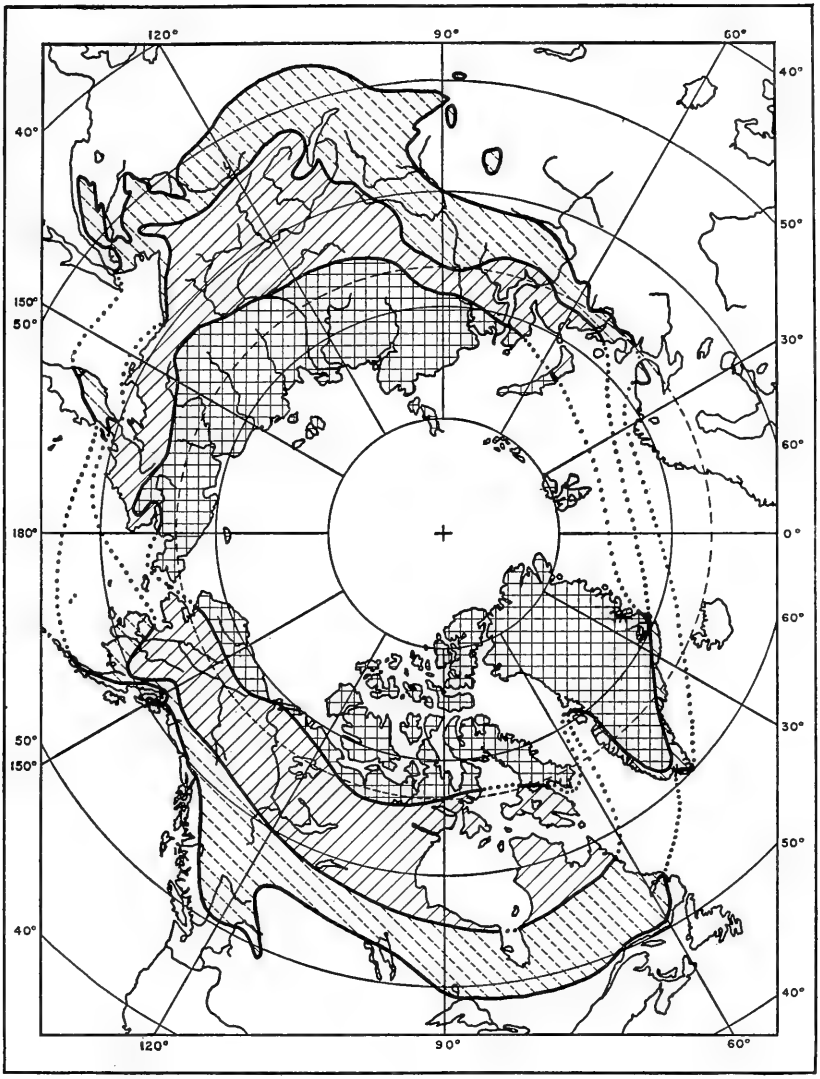
PERMAFROST

The term *permafrost* was proposed and defined by Muller (1945). A longer but more correct English phrase is "perennially frozen ground" (Taber, 1943a). The difficulties of the present terminology are discussed by Bryan (1946a, b), who proposed a new set of terms. These are discussed by representative geologists and engineers (Bryan, 1948). Such terms as cryopedology, congeliturbation, congelifraction, and cryoplanation are being accepted by some geologists (Judson, 1949; Denny and Sticht, unpublished manuscript; Cailleux, 1948; Troll, 1948) in order to attempt standardization of the terms regarding perennially frozen ground and frost action. The term permafrost has been widely adopted by agencies of the United States Government, by private organizations, and by scientists and laymen alike. Its use is continued in this chapter because it is simple, euphonious, and easily understood by all.

EXTENT

Much of northern Asia and northern North America contains perennially frozen ground (Fig. 1) (Sumgin, 1947; Muller, 1945; Obruchev, 1945; Troll, 1944; Taber, 1943a; Cressey, 1939).

The areal subdivision of permafrost into continuous, discontinuous, and sporadic bodies is already possible on a small scale for much of



Double hatching: Approximate extent of continuous permafrost. Ground temperature at a depth of 30 to 50 feet generally below $-5°$ C.

Diagonal hatching: Approximate extent of discontinuous permafrost. Ground temperature in permafrost at a depth of 30 to 50 feet generally between $-5°$ and $-1°$ C.

Dotted diagonal hatching: Approximate extent of sporadic permafrost. Ground temperature in permafrost at a depth of 30 to 50 feet generally above $-1°$ C.

Reliability: Eurasia, good; Alaska, fair; all other, poor. (Eurasia after Sumgin and Petrovsky, 1940, courtesy of I. V. Poiré.)

Fig. 1. Areal distribution of permafrost in the Northern Hemisphere.

Asia, but as yet for only part of North America. Refinements in delineations of these boundaries are being made each year. The southern margin of permafrost is known only approximately, and additional isolated bodies are being discovered as more detailed work is undertaken. The southern margin of permafrost has receded northward within the last century (Obruchev, 1946).

Permafrost is absent or thin under some of the existing glaciers, and it may be absent in areas recently exhumed from ice cover.

A greater extent of permafrost in the recent geologic past is known by inference from phenomena now found to be associated with permafrost (H. T. U. Smith, 1949b; Horberg, 1949; Richmond, 1949; Schafer, 1949; Cailleux, 1948; Poser, 1947a, b; Troll, 1947, 1944; Zeuner, 1945; Weinberger, 1944). Some of the more important phenomena are fossil ground-ice wedges, solifluction deposits, block fields and related features, involutions in the unconsolidated sediments, stone rings, stone stripes and related features, and asymmetric valleys (H. T. U. Smith, 1949b). The presence of permafrost in earlier geologic periods can be inferred from the cold climates accompanying many periods of glaciation and from fossil periglacial forms.

In the Southern Hemisphere permafrost is extensive in Antarctica and probably occurs locally in some of the higher mountains elsewhere, but its actual extent is unknown.

Thickness

Permafrost attains its greatest known thickness of about 2,000 feet (620 meters) at Nordvik in northern Siberia (I. V. Poiré, oral communication). Werenskiold (1923) reports a thickness of 320 meters (1,050 feet) in the Sveagruvan coal mine in Lowe Sound, Spitzbergen. In Alaska its greatest known thickness is about 1,000 feet, south of Barrow.

Generally it can be said that the frozen zone thins abruptly to the north under the Arctic Ocean. It breaks into discontinuous and sporadic bodies as it gradually thins to the south (Fig. 2) (Muller, 1945; Taber, 1943a; Cressey, 1939).

In areas of comparable climatic conditions today, permafrost is much thinner in glaciated areas than in non-glaciated areas (Taber, 1943a).

Unfrozen zones within perennially frozen ground are common near the surface (Muller, 1945) and are reported to occur at depth (Taber, 1943a; Cressey, 1939). They have been interpreted as indicators of climatic fluctuations (Muller, 1945; Cressey, 1939), or as permeable water-bearing horizons (Taber, 1943a).

Temperature

The temperature of perennially frozen ground below the depth of seasonal change (level of zero annual amplitude) (Muller, 1945) ranges from slightly less than 0° C. to about −12° C. (I. V. Poiré, oral communication). In Alaska the minimum temperature found to date is −9.6° C. at a depth of 100 to 200 feet in a well about 40 miles southwest of Barrow (J. H. Swartz, 1948, written communication). Representative temperature profiles in areas of (1) continuous permafrost are shown in Fig. 3*a;* of (2) discontinuous permafrost in Fig. 3*b;* and of (3) sporadic bodies of permafrost in Fig. 3*c*.

Temperature gradients from the base of permafrost up to the depth of minimum temperature vary from place to place and from time to time. Measurement of four wells in northern Alaska resulted in gradients between 120 and 215 feet per centigrade degree (data of J. H. Swartz, G. R. MacCarthy, and R. F. Black).

The shape of a temperature curve indicates pergelation or depergelation (aggradation or degradation of permafrost) (Muller, 1945; Taber, 1943a). Some deep temperature profiles have been considered by Russian workers to reflect climatic fluctuations in the recent geologic past. No known comprehensive mathematical approach has been attempted to interpret past climates from these profiles, although it seems feasible. Some of the effects of Pleistocene climatic variations on geothermal gradients are discussed by Birch (1948).

Character

As permafrost is defined as a temperature phenomenon, it may encompass any type of natural or artificial material, whether organic or inorganic. Generally, permafrost consists of variable thicknesses of perennially frozen surficial unconsolidated materials, bedrock, and ice. Physical, chemical, or organic composition, degree of induration, texture, structure, water content, and the like, range widely and are limited only by the extremes of nature or the caprice of mankind. For example, perennially frozen mammals, rodents, bacteria, artifacts, beds of sand and silt, lenses of ice, beds of peat, and varied junk piles, such as kitchen-middens, mine dumps, and ships' refuse heaps, are individual items that collectively can be lumped under the term permafrost.

Ground perennially below freezing but containing no ice has been called "dry permafrost" (Muller, 1945).

Permafrost containing much ice is abundant, particularly in poorly drained fine-grained materials. The ice forms thin films, grains, fill-

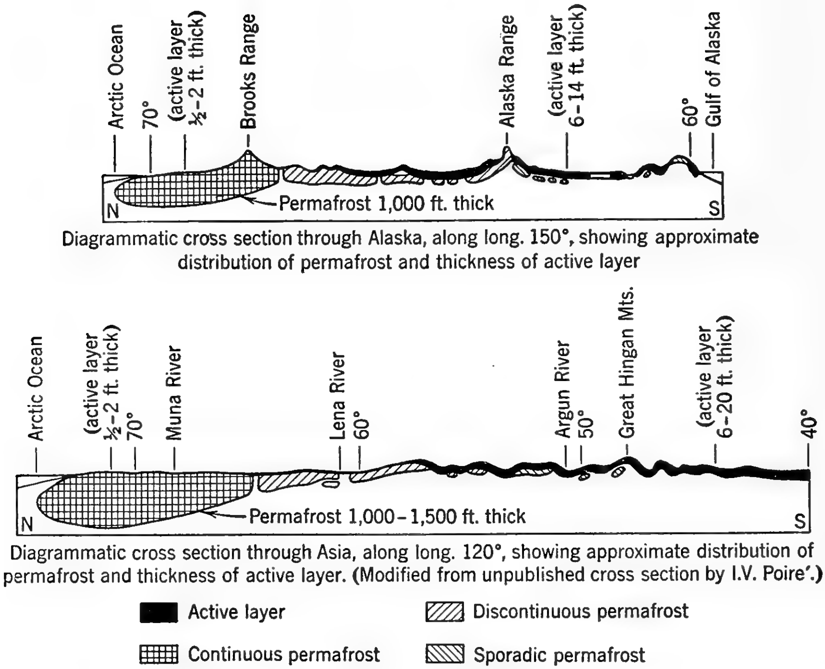


FIG. 2. Representative cross sections of permafrost areas in Alaska and Asia.

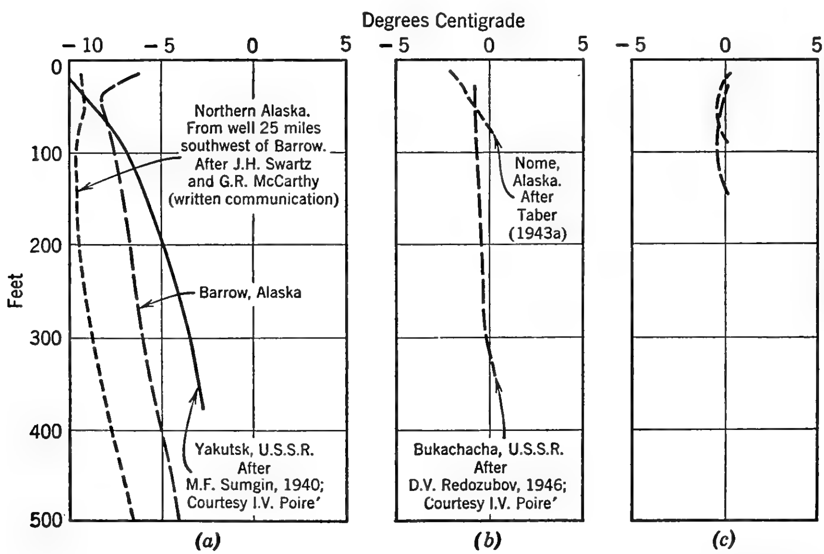


FIG. 3. (*a*) Representative temperature profiles in areas of continuous permafrost. (*b*) Representative temperature profiles in areas of discontinuous permafrost. (*c*) Hypothetical temperature profiles in areas of sporadic permafrost.

ings, veinlets, large horizontal sheets, large vertical wedge-shaped masses, and irregular masses of all sizes. Many masses of clear ice are arranged in geometric patterns near the surface, that is, polygonal ground and honeycomb structure. The ice may be clear, colorless, yellow, or brown. In many places it contains numerous air bubbles, oriented or unoriented, and silt, clay, or organic materials. Size, shape, and orientation of the ice crystals differ widely. Discordant structures in sediments around large masses of ice are evidences of growth (Taber, 1943a; Leffingwell, 1919).

Relation to Terrain Features

In the continuous zone of permafrost the upper limit (permafrost table, Muller, 1945) is generally within a few inches or 2 feet of the surface. Large lakes and a few large rivers lie in thawed areas slightly larger than the basins they occupy (Black and Barksdale, 1949; Muller, 1945). Well-drained coarse-grained materials may thaw annually to a depth of 6 feet. Poorly drained fine-grained materials protected from insolation and insulated with moss and other vegetation may thaw annually to a depth of only 4 inches.

In the discontinuous zone most major rivers and lakes are not underlain by permafrost, and it may be absent in the tops of some well-drained low hills. Seasonal thaw (active layer, Muller, 1945) penetrates 1 foot to 10 feet, depending on insulation, insolation, drainage, and type of material.

Sporadic bodies of permafrost may be relics below the active layer or may be forming in favorable situations in poorly drained fine-grained materials on north-facing slopes. In the zone of sporadic permafrost the active layer may or may not reach the permafrost table, and it ranges between 2 and 14 feet in thickness.

Generally the depth of thaw is at a minimum in northern latitudes and increases to the south. It is at a minimum in peat or highly organic sediments and increases in clay, silt, and sand to a maximum in gravelly ground or exposed bedrock. It is less at high altitudes than at low altitudes; less in poorly drained ground than in dry well-drained ground; at a minimum under certain types of tundra and increases in thickness under areas of bog shrubs, black spruce, larch, white spruce, birch, aspen, and poplar to a maximum under tall pines. It is less in areas of heavy snowfall; less in areas with cloudy summers; and less on north-facing slopes (Muller, 1945; Troll, 1944; Taber, 1943a).

Works of man commonly upset the natural thermal equilibrium and may tend to destroy permafrost or to aid in building it up. Most roads, runways, and other structures on the surface or in the ground generally have lower permafrost tables than undisturbed natural areas adjacent to them. Structures above the ground and insulated from the ground protect the surface from insolation and commonly produce higher permafrost tables.

ORIGIN

The origin of perennially frozen ground is discussed by Muller (1945), Zeuner (1945), Taber (1943a), Cressey (1939), Nikiforoff (1932), Leffingwell (1919), and others. Generally it can be stated that most sporadic bodies of permafrost are relics of colder climates. Discontinuous bodies of permafrost are largely relics, but under favorable conditions they can grow in size, and new deposits are being perennially frozen. In areas of continuous permafrost, heat is being dissipated actively from the surface of the earth to the atmosphere, and new deltas, bars, landslides, mine tailings, and other deposits are being pergelated (incorporated in the permafrost) (Bryan, 1946a).

Local surface evidences indicate that heat, in some places at least, is being absorbed at the base of permafrost faster than it is being dissipated at the surface (Hopkins, 1949; Young, 1918). Hence the cold reserve is being lessened, and the thickness of permafrost is decreasing from the base upward.

The mean annual air temperature required to produce permafrost undoubtedly varies many degrees because of local conditions. Generally it is given as 30° to 24° F.; theoretically permafrost can form above 32° F. (Theis, unpublished manuscript), and apparently it is doing so locally in parts of southwest Alaska where poor drainage, abundant vegetation, cloudy summers, and low insolation are found (S. Abrahamson, oral communication).

The relative effects of past climates have been inferred qualitatively from present temperature profiles and indirectly through a study of past deposits, pollen analysis, vegetal changes, structural soils, blockfields, etc.

The origin of large, clear ice masses in the permafrost is a special problem in itself. Numerous theories are extant, and one or more may apply to a particular mass of ice (Taber, 1943a; Leffingwell, 1919).

GEOLOGIC RAMIFICATIONS

Throughout the Arctic and sub-Arctic the role of permafrost is extremely important. As an impervious horizon in continuous permafrost zones, it exerts a drastic influence on surface waters, completely prevents precipitation from entering the natural ground-water reservoirs, and commonly causes a concentration of organic acids and of mineral salts in suprapermafrost water. In discontinuous permafrost zones, and less so in areas of sporadic permafrost bodies, ground-water movements are interrupted or channelized. Quality of water, too, can be materially affected by the storage for centuries and subsequent release by thawing of organic and inorganic materials (Kaliaev, 1947). In fact, our present conceptions of ground-water reservoirs, ground- and surface-water movements, infiltration, quality of water, and so on, must be reconsidered in light of another new geologic formation, generally not uniform in composition or distribution, that transcends all rock and soil formations. Furthermore, it must be considered as much in the light of past as of present conditions.

It is well-known that in cold climates physical disintegration (frost-splitting, congelifraction) plays a more important role than chemical weathering. The repeated freezing of water-saturated materials and the growth of ice crystals in numerous small pores, cracks, joints, cleavage planes, or partings is by far the most important destructive process. Taber (1943a) has shown that, without water, disintegration is generally much slower. Permafrost is one of the most important agents in keeping the soils supersaturated (containing more water than pore space—a suspension) and in keeping many rock fragments wet.

It is less widely known that mass-wasting processes in the Arctic and sub-Arctic are instrumental in the transport of tremendous volumes of material. With the exception of unbroken bedrock, the materials on the surface of slopes greater than 1° to 3° are on the move everywhere in summer. The amount of material involved and the rapidity of such movements impress all who have studied them (Washburn, 1947).

Permafrost, on thawing slightly in summer, supplies a lubricated surface and additional water to some materials probably already saturated. Hence solifluction, mud flows, and other gravity movements take place with ease and, in favorable locations, even supply material to streams faster than the streams can remove it (Wahrhaftig, 1949). Bryan (1949) has coined the term "cryoplanation" to cover such processes, including also frost-heaving normal to slopes and settling vertically, which in the Arctic are instrumental in reducing the landscape to long, smooth slopes and gently rounded forms. Such physiographic processes are only partly understood and their effects only qualitatively known (Bryan, 1949).

Permafrost, by aiding in maintaining saturated or supersaturated conditions in surficial materials, indirectly aids in frost-stirring (congeliturbation), frost-splitting, and mass-wasting processes so that, in places, bedrock is disintegrated, reduced in size, thoroughly mixed, and rapidly transported, the result being a silt-sized sediment that is widespread in the Arctic. Disagreement exists among various authors (Bryan, 1949; Hopkins, 1949; P. S. Smith, unpublished manuscript; Zeuner, 1945; Taber, 1943a; Tuck, 1940) whether some of the material is derived from eolian, lacustrine, or local frost-splitting and mass-wasting processes. Size-distribution curves, mineral comparisons, chemical analyses, comparisons with glacial materials and with organic materials, etc., have been used by various investigators to prove their point, but the differences of opinions have by no means been resolved.

Frost action (frost-heaving, frost-stirring, and frost-splitting) and gravity movements result in many surface forms that are found most abundantly in areas of permafrost: *strukturboden,* involutions, frost boils, hummocks, altiplanation terraces, terrecettes, and soil stripes (Judson, 1949; Richmond, 1949; Schafer, 1949; Smith, 1949; Cailleux, 1948; Troll, 1948, 1947, 1944; Washburn, 1947; Conrad, 1946; Zeuner, 1945; Taber, 1943a; Sharp, 1942b; Gatty *et al.,* 1942; Steche, 1933; Högbom, 1914). Annual freezing in permafrost areas also forces changes in surface and ground-water migration and commonly results in pingos, frost blisters, ice mounds, icings, aufeis, and other related forms (Muller, 1945; Troll, 1944; Sharp, 1942a; Mullis, 1930). Many of the forms produced by frost action and seasonal freezing are closely related in character and origin; however, the lack of a standardized terminology for these features produces a perplexing picture.

Little can be said quantitatively regarding the importance of frost action (and indirectly permafrost) in past sediments and soils (Zeuner, 1945). Throughout the world, fossil deposits of former glaciers have been found in the stratigraphic column. They indicate many periods of glaciation and, hence, cold climates. Undoubtedly permafrost was present during those times. Fossil forms derived from frost and permafrost are known (Horberg, 1949; Judson, 1949; Richmond, 1949; Schafer, 1949; H. T. U. Smith, 1949b; Wahrhaftig, 1949; Zeuner, 1946, 1945; Troll, 1944), and they provide data on the processes producing the surficial materials and the environment of deposition. These features are only now being recognized and studied in the detail that is warranted (Bryan, 1949).

Permafrost throughout the world has provided an outstanding wealth of material for paleontologists and archeologists. In perennially frozen Alaskan placers alone, investigators have found more than 27 different plants (Chaney and Mason, 1936), including whole forests of buried stumps (Giddings, 1938); numerous iron and other bacteria; algae; 87 species of diatoms (Taber, 1943a); bones of at least 20 species of large mammals, represented by tens of thousands of specimens (Taber, 1943a; Wilkerson, 1932); numerous species of rodents; and a few species of mollusks, sponges, and insects (Taber, 1943a). Permafrost in Siberia has been a storehouse for Pleistocene mammals (Tolmachoff, 1929).

Permafrost upsets many readings taken by geophysicists in determining the internal constitution of the earth. Velocities of seismic waves, for instance, are materially increased by frozen ground containing much ice and may result in considerable errors in determinations of depths. Although the actual increases are not definitely known, they probably fall within the range of 1,000 to 8,000 feet per second. Unfortunately the lower contact of permafrost causes, with present equipment, no satisfactory reflections or refractions. Seismic methods cannot be used to determine the thickness or variability of the zone distorting the seismic waves. Difficulties in drilling, preparing the explosive charges, checking the ground waves, and getting interpretable effects are augmented in permafrost areas.

Electrical methods, particularly the resistivity methods, have given promise of solving some of the difficulties in determining the extent and thickness of permafrost (Enenstein, 1947; Swartz and Shepard, 1946; Muller, 1945; and Joestings, 1941). Generally resistivities of frozen silt and gravel are several thousand ohms higher than comparable unfrozen materials and may be 20 to 120 times as high (Swartz and Shepard, 1946; Joestings, 1941). However, it is well-known that the type of material is less important than the amount of unfrozen ground water and dissolved salts within the material. Even in frozen ground these factors are so variable that resistivity data can be interpreted with reliability only in the hands of experienced men and generally only in areas where some positive checks can be made through drilling.

Sumgin and Petrovsky (1947) discuss a new radio-wave technique used where permafrost is below $-5°$ C.

ENGINEERING SIGNIFICANCES

In Alaska during World War II the difficulties encountered by our armed forces in obtaining permanent water supplies and in constructing runways, roads, and buildings in permafrost areas focused attention on permafrost as no other difficulties could have (Wilson, 1948; Jaillite, 1947; Barnes, 1946; Taber, 1943b). Only then did most of us realize that in Russia similar difficulties with railroads, roads, bridges, houses, and factories had impeded colonization and development of the north for decades. Now with the recent progress in aviation, and because of the strategic importance of the north, active construction and settlement for military and civilian personnel must increase, and the problems of permafrost must be solved.

Fortunately we can draw on the vast experience of our northern neighbors. Their engineers have shown that it is

> . . . a losing battle to fight the forces of frozen ground simply by using stronger materials or by resorting to more rigid designs. On the other hand, the same experience has demonstrated that satisfactory results can be achieved and are allowed for in the design in such a manner that they appreciably minimize or completely neutralize and eliminate the destructive effect of frost action . . . Once the frozen ground problems are understood and correctly evaluated, their successful solution is for the most part a matter of common sense whereby the frost forces are utilized to play the hand of the engineer and not against it. . . . it is worth noting that in Soviet Russia since about 1938 all governmental organizations, municipalities, and cooperative societies are required to make a thorough survey of the permafrost conditions according to a prescribed plan before any structure may be erected in the permafrost region. [Muller, 1945, pp. 1–2, 85–86.]

Specifically we must think of permafrost in construction of buildings, roads, bridges, runways, railroads, dams, and reservoirs, in problems of water supply, sewage disposal, telephone lines, drainage, excavation, ground storage, and in many other ways. Permafrost can be used as a construction material or as a base for construction, but steps must be taken to insure its stability. Otherwise it must be destroyed and appropriate steps taken to prevent it from returning.

BIOLOGIC SIGNIFICANCES

Permafrost, by means of its low temperature and ability to prevent runoff, is a potent factor that aids in controlling vegetal growth in the Arctic and sub-Arctic (Mosley, 1937). Many places have semi-arid climate yet have luxuriant growths of vegetation because the permafrost prevents the loss of precipitation through underground drainage (low evaporation is possibly as important). Such conditions are natural breeding environments for mosquitoes and other insects.

Conversely, luxuriant growths of vegetation, by insulating the permafrost in summer, prevent deep thawing, restrict food supplies, and augment cold soil temperatures. Hence those species with deep root systems, such as certain trees, are dwarfed or absent.

Raup (1941, 1947) points out that much of arctic soil is unstable because of frost action (commonly associated with permafrost) and that standard biological methods describing plant communities do not apply. The normal associations have been greatly disturbed, special communities for different frost forms can be identified, and above all the plant communities must be described on the basis of their physical habitat.

Permafrost probably controls the distribution of some animal species, such as the frogs or toads, that require thawed ground into which they can burrow for the winter. Foxes can have dens only in dry elevated places where the depth of thaw is 2 feet or more. Similarly, permafrost affects worms, burrowing insects, and other animals that live in the ground.

Indirectly, permafrost, by exercising some control on types of vegetation, that is, tundra *vs.* forest, also determines the distribution of grazing animals such as the reindeer and barren-ground caribou.

FACTORS AFFECTING PERMAFROST

Most major factors affecting permafrost are recognized qualitatively, but none is well-known quantitatively. These factors are easily visualized by turning to the original definition of the term permafrost. As permafrost is fundamentally a temperature phenomenon, we may think of it as a negative temperature produced by climate in material generally of heterogeneous composition. Permafrost is produced because, through a combination of many variable factors, more heat is removed from a portion of the earth during a period of 2 or more years than is replaced. Hence a cold reserve is established.

Basically the process can be reduced to one of heat exchange between the sun, the atmosphere, and the earth. The sun, through solar radiation (insolation), and the interior of the earth, primarily through conduction, supply practically all primary heat to the surface of the earth (biological processes, natural or artificial fires, chemical reactions, cosmic or other radiations excepted). This primary heat is dissipated to the atmosphere and to outer space by conduction, radiation, convection, and evaporation. The atmosphere by warm winds and precipitation also distributes secondary heat to the surface of smaller areas.

We know that earth temperatures at the depth of seasonal change are in most places within a few degrees of the mean annual air temperature, and that a geothermal gradient is established from the surface to the interior of the earth. The geothermal gradient at any one place is relatively fixed from year to year, though it varies from place to place and has changed markedly during geologic time. It is generally considered as 1° F. for each 60 to 110 feet of depth in sedimentary rock in the United States (Orstrand, 1939); possibly 0.1 to 0.2 calorie per square centimeter per day is transmitted to the surface from the interior (Theis, unpublished manuscript). In contrast the sun supplies possibly as much as several hundred calories per square centimeter per day to the surface, depending primarily on the season and secondarily on cloudiness, humidity, altitude, latitude, etc. This period of rapid heating, however, is very short in the Arctic, and for many months heat is dissipated to the atmosphere and outer space. When dissipation of heat outweighs input, a cold reserve is produced. If the cold reserve remains below freezing for more than two years, it is called permafrost.

Although the fundamental thesis of the problem is simple, its quantitative solution is exceedingly complex. In only a few isolated areas in the Arctic do we know anything of the geothermal gradients in and below permafrost. The climate (including insolation) is so incompletely known that at present it is not possible to rate climatic factors except in a general way as they effect primary or secondary heat or dissipation of heat (Lane, 1946). Thus it is well-known that the following conditions tend to produce permafrost:

(1) Long, cold winters and short, cool summers.
(2) Low precipitation the year around and especially low snowfall.
(3) Clear winters and cloudy summers.
(4) Rapid evaporation the year around.
(5) Strong, cold winds in summer and winter.
(6) Low insolation.

The materials involved have different specific heats and different heat conductivities (Shannon and Wells, 1947; Muller, 1945; W. O. Smith, 1939, 1942). Chemical and physical properties vary widely, yet are of primary importance (W. O. Smith, 1942; Taber, 1930a, b). Water transmits heat about 25 times as fast as air, and ice 4 times as fast as water. Thus, poorly drained silt and muck are much more easily frozen than dry, coarse-grained gravel. W. O. Smith (1942) points out the marked effect of soil structures and of architecture of pore space on thermal resistance in natural soils.

The dissipating surface of the earth is even more complex and more changeable. Water-saturated frozen vegetation and soil (bare of snow) in winter can act as an active conductor, whereas lush, dry vegetation and dry porous soil in summer is an excellent insulator.

Black-top pavements are good conductors and heat absorbers in summer and can destroy permafrost. An elevated and insulated building with circulating air beneath can be more than enough to unbalance the thermal regime of the ground toward permafrost. Under fixed laboratory conditions heat conductivities of some earth materials are known, but the quantitative effect in nature of variable moisture conditions and of changing vegetation is not. Changes in the volume, composition, or temperature of ground water or surface runoff have effects as yet little known qualitatively or quantitatively.

All these factors must be considered to be in a delicate balance between freezing and thawing. It is to be emphasized that the thermal regime is not uniform, but changing from hour to hour, day to day, week to week, year to year, and cycle to cycle. Specifically we must think in terms of geographic position, topography, lithology, structure, and texture of soils and bedrock, hydrology, geothermal gradients, thermal conductivities, vegetation, climate (temperature, precipitation, cloudiness, wind, insolation, evaporation), and cultural features. What effect cosmic dust clouds, changes in carbon dioxide content of the atmosphere, inclination of the earth's axis, eccentricity of the earth's orbit, sun spots, etc., have on permafrost can only be surmised as they affect insolation and dissipation of the earth's heat.

PRACTICAL APPLICATION AND SOLUTION OF THE PROBLEMS

In a permafrost area, it is imperative that the engineer have a complete understanding of the extent, thickness, temperature, and character of the permafrost and its relation to its environment before construction of any buildings, towers, roads, bridges, runways, railroads, dams, reservoirs, telephone lines, utilidors, drainage ditches and pipes, facilities for sewage disposal, establishments for ground-water supply, excavations, foundation piles, or other structures. The practical importance of the temperatures of permafrost cannot be overemphasized. A knowledge of whether permafrost is actively building up, is stabilized, or is being destroyed is essential in any engineering problem. Past experience has amply demonstrated that low cost or high cost, success or failure, is commonly based on a complete understanding of the problems to be encountered. Once the conditions are evaluated, proper precautions can be taken with some assurance of success.

Muller (1945) gives comprehensive outlines of general and detailed permafrost surveys as adapted to various engineering projects. These outlines include instructions for the planning of the surveys, method of operation, and data to be collected. Rarely does the geologist or engineer or both on a job encounter "cut and dried" situations, and it is obvious that personal discretion must be exercised in modifying the outlines to meet the situation at hand.

In reconnaissance or preliminary survey to select the best site for construction in an unknown area, it is recommended that the approach be one of unraveling the natural history of the area. Basically the procedure is to identify each land form or terrain unit and determine its geologic history in detail. Topography, character and distribution of materials, permafrost, type and distribution of vegetation, hydrology, and climate are studied and compared with known areas. Then inferences, deductions, extrapolations, or interpretations can be made with reliability commensurate with the type, quality, and quantity of original data.

Thus the solution of the problems depends primarily on a complete understanding of the thermal regime of the permafrost and active layer. No factor can be eliminated, but all must be considered in a quantitative way. It is understandable that disagreement exists on the mean annual air temperature needed to produce permafrost. Few, if any, areas actually have identical conditions of climate, geology, and vegetation; hence, how can they be compared directly on the basis of climate alone? Without doubt the mean annual temperature required to produce permafrost depends on many factors and varies at least several degrees with variations in these factors. For practical purposes, however, units (terrain units) in the same climate or in similar climates may be separated on the basis of geology and vegetation. Thus there is a basis for extrapolating known conditions into unknown areas.

The advantages of aerial reconnaissance and study of aerial photographs for preliminary site selecting are manifold. Aerial photographs in the hands of experienced geologists, soils engineers, and botanists can supply sufficient data to determine the best routes for roads and railroads, the best airfield sites, and data on water supply, construction materials, permafrost, trafficability conditions, camouflage, and other problems. Such an approach has been used with success by the Geological Survey and other organizations and individuals (Black and Barksdale, 1949; Wallace, 1948; Woods *et al.*, 1948; Pryor, 1947).

Emphasis is placed on the great need for expansion of continuing applied and basic research projects as outlined by Jaillite (1947) and referred to by Muller (1945) for a clearer understanding and evaluation of the problems.

Recognition, Prediction, and Instrumentation

Recognition and prediction of permafrost go hand in hand in a permafrost survey. If natural exposures of permafrost are not available along cut banks of rivers, lakes, or oceans, it is necessary to dig test pits or drill holes in places to obtain undisturbed samples for laboratory tests and to determine the character of the permafrost.

Surface features can be used with considerable degree of accuracy to predict permafrost conditions if the origin of the surface forms are clearly understood. Vegetation alone is not the solution, but it can be used with other factors to provide data on surficial materials, surface water, character and distribution of the permafrost, and particularly on the depth of the active layer (Denny and Raup, unpublished manuscript; Stone, 1948; Muller, 1945; Taber, 1943a). Cave-in or thermokarst lakes (thaw sinks, Hopkins, 1949; Black and Barksdale, 1949; Wallace, 1948; Muller, 1945) and ground-ice mounds (Sharp, 1942a) are particularly good indicators of fine-grained materials containing much ground ice. Polygonal ground can be used with remarkable accuracy also if the type of polygonal ground and its origin are clearly known. Numerous types of *strukturboden,* polygonal ground, and related forms have been described and their origins discussed (Richmond, 1949; Cailleux, 1948; Washburn, 1947; Troll, 1945; Sharp, 1942b; Högbom, 1914). The type of ice-wedge polygon described by Leffingwell (1919) can be delimited from others on the basis of surface expression. The author's own work in northern Alaska (1945–1948) revealed that the polygons go through a cycle that can be described as youth, maturity, and old age—from flat surface with cracks to low-centered polygons and, finally, to high-centered polygons. Size and shape of polygons, widths and depths of troughs or cracks, presence or absence of ridges adjacent to the troughs, type of vegetation, and other factors all provide a clue to the size-grade of surficial materials and the amount of ice in the ground. Frost mounds, frost blisters, icings, gullies, and many other surficial features can be used with reliability if all factors are considered and are carefully weighed by the experienced observer. Geophysical methods of locating permafrost have given some promise (Sumgin and Petrovsky, 1947; Enenstein, 1947; Swartz and Shepard, 1946; Muller, 1945; Joestings, 1941). Various temperature-measuring and -recording devices are employed. Augers and other mechanical means of getting at the permafrost are used (Muller, 1945).

CONSTRUCTION

Two types of construction methods are used in permafrost areas (Muller, 1945). In one, the passive method, the frozen-ground conditions are left undisturbed or provided with additional insulation, so that the heat from the structure will not cause any thawing of the underlying ground and weaken its stability. In the other method, the active method, the frozen ground is thawed prior to construction, and steps are taken to keep it thawed or to remove it and to use materials not subject to heaving and settling as a result of frost action. A preliminary examination, of course, is necessary to determine which procedure is more practicable.

Permafrost can be used as a construction material (if stress or load does not exceed plastic or elastic limit), removed before construction, or controlled outside the actual construction area. Muller (1945) has shown that it is best to distinguish (*a*) continuous areas of permafrost from (*b*) discontinuous areas and from (*c*) sporadic bodies. Russian engineers recommend that in (*a*) only the passive method of construction be used; in (*b*) or (*c*) either the passive or active method be used, depending on thickness and temperature of the permafrost. Detailed information and references on the construction of buildings, roads, bridges, runways, reservoirs, airfields, and other engineering projects are presented by Hardy and D'Appolonia (1946); Corps of Engineers (1946, 1945); Muller (1945); Huttl (1948); and Zhukov (1946). Refinements of the techniques and data on Alaskan research projects (Wilson, 1948; Jaillite, 1947; Barnes, 1946) are contained largely in unpublished reports of various federal agencies.

Eager and Pryor (1945) have shown that road icings are more common in areas of permafrost than elsewhere. They, Tchekotillo (1946), and Taber (1943b) discuss the phenomena of icings, classify them, and describe various methods used to prevent or alleviate icing.

One of the major factors to consider in permafrost is the water content. Methods of predicting by moisture diagrams the amount of settling of buildings on thawing permafrost are presented by Fedosov (1942).

Emphasis should be placed again on the fact that permafrost is a temperature phenomenon that occurs naturally in the earth. If man disturbs the thermal regime knowingly or unknowingly, he must suffer the consequences. Every effort should be made to control the thermal regime, to promote pergelation or depergelation as desired. Generally the former is difficult near the southern margin of permafrost. If the existing climate is not cold enough to insure that the permafrost remain frozen, serious consideration should be given to artificial freezing in those places where permafrost must be utilized as a construction material. Techniques that were used at Grand Coulee Dam or on Hess Creek (Huttl, 1948) can be modified to fit the situation. It should be borne in mind that the refrigerating equipment need be run only for a matter of hours during the summer after the ground has been refrozen and vegetation or other means of natural insulation have been employed. Bad slides on roads and railroads, settling under expensive buildings, loosening of the foundations of dams, bridges, towers, and the like probably can be treated by refreezing artificially at less cost than by any other method. In fact the day is probably not far off when airfields of Pycrete (Perutz, 1948) or similar material will be built in the Arctic where no construction materials are available.

Where seasonal frost (active layer) is involved in construction, the engineer is referred to the annotated bibliography of the Highway Research Board (1948) and to such reports as that of the Corps of Engineers (1945, 1946, 1947).

Water Supply

Throughout permafrost areas one of the main problems is a satisfactory source of large amounts of water. Problems encountered in keeping the water liquid during storage and distribution or in its purification are beyond the scope of this report. Small amounts of water can be obtained generally from melted ice or snow. However, a large, satisfactory, annual water supply in areas of continuous permafrost is to be found only in deep lakes or large rivers that do not freeze to the bottom. Even then the water tends to have considerable mineral hardness and organic content. It is generally not economical to drill through 1,000 to 2,000 feet of permafrost to tap ground-water reservoirs beneath, although artesian supplies have been obtained under 700 feet of permafrost (Dementiev and Tumel, 1946) and under 1,500 feet of permafrost (Obruchev, 1946).

In areas of discontinuous permafrost, large annual ground-water supplies are more common either in perched zones on top of permafrost or in non-frozen zones within or below the permafrost (Cederstrom, 1948; Péwé, 1948b).

Annual water supply in areas of sporadic permafrost bodies normally is a problem only to individual householders and presents only a little more difficulty than finding water in comparable areas in temperate zones.

Surface water as an alternate to ground water can be retained by earthen dams in areas of permafrost (Huttl, 1948).

Throughout the Arctic, however, the quality of water is commonly poorer than in temperate regions. Hardness, principally in the form of calcium and magnesium carbonate and iron or manganese, is common. Organic impurities and sulphur are abundant. In many places ground water and surface water have been polluted by man or organisms.

Muller (1945) presents a detailed discussion of sources of water and the engineering problems in permafrost areas of distributing the water. Joestings (1941) describes a partially successful method of locating water-bearing formations in permafrost with resistivity methods.

Sewage Disposal

Sewage disposal for large camps in areas of continuous permafrost is a most difficult problem. Wastes should be dumped into the sea, as no safe place exists on the land for their disposal in a raw state. As chemical reaction is retarded by cold temperatures, natural decomposition and purification through aeration does not take place readily. Large streams that have some water in them the year around are few and should not be contaminated. Promiscuous dumping of sewage will lead within a few years to serious pollution of the few deep lakes and other areas of annual surface-water supply. Burning is costly. No really satisfactory solution is known. In discontinuous and sporadic permafrost zones, streams are larger and can handle sewage more easily, yet even there sewage disposal still remains in places one of the most important problems.

Agriculture

Permafrost as a cold reserve has a deleterious effect on the growth of plants. However, as an impervious horizon it tends to keep precipitation in the upper soil horizons, and in thawing provides water from melting ground ice. Both deleterious and beneficial effects are negligible after one or two years of cultivation, as the permafrost table thaws, in that length of time, beyond the reach of roots of most annual plants (Gasser, 1948).

Farming in permafrost areas that have much ground ice, however, can lead to a considerable loss in time and money. Sub-Arctic farming can be done only where a sufficient growing season is available for plants to mature in the short summers. Such areas are in the discontinuous or sporadic zones of permafrost. If the land is cleared of its natural insulating cover of vegetation, the permafrost thaws. Over a period of 2 to 3 years, large cave-in lakes have developed in Siberia, and pits and mounds have formed in Alaska (Péwé, 1948a, 1949;

Rockie, 1942). The best solution is to select farm lands in those areas free of permafrost or free of large ground-ice masses (Tziplenkin, 1944).

Mining

In Alaska, placer miners particularly, and lode miners to a lesser extent, have utilized permafrost or destroyed it as necessary since it was first encountered. Particularly in placer mining, frozen ground has been the factor that has made many operations uneconomic (Wimmler, 1927). These problems cannot be treated lightly.

In the early part of the century, when gold was being mined so profitably at Dawson, Fairbanks, Nome, and other places in northern North America, it was common for miners to sink shafts more than 100 feet through frozen muck to the gold-bearing gravels (P. S. Smith, unpublished manuscript). These shafts were sunk by steam jetting or by thawing with fires or hot rocks. If the muck around the shafts or over the gravels thawed, the mines had to be abandoned.

Now, with the advent of dredges, such ground is thawed, generally with cold water, one or more years in advance of operations. The technique is one of drilling holes through the permafrost at regular intervals of possibly 10 to 30 feet, depending on the material, and forcing cold water through the permafrost into underlying permeable foundations or out to the surface through other holes. Hot water and steam, formerly used, are uneconomical and inefficient. Where thick deposits of overburden cover placers, they are removed commonly by hydraulicking. Summer thaw facilitates the process (Patty, 1945).

Permafrost is commonly welcomed by the miners in lode mining, as it means dry working conditions. Its effect on mining operations other than maintaining cold temperatures in the mine is negligible unless it contains aquifers. Because of cold temperatures, sealing such aquifers with cement is difficult, and other techniques must be used as the situation demands.

Some well drilling in permafrost requires modifications of existing techniques and more careful planning for possible exigencies (Fagin, 1947). Difficulty may be encountered in getting proper foundations for the rig. In rotary drilling, difficulty may be experienced in keeping drilling muds at the proper temperature, in finding adequate water supplies, or in finding proper local material for drilling muds. In shallow holes particularly, the tools will "freeze in" after a few hours of idleness. Cementing of casings is costly and very difficult, as concrete will not set in subfreezing temperatures. Deep wells below the permafrost may encounter high temperatures (100° to 150° F.), and the hot drilling muds on returning to the surface thaw the permafrost around the casing and create a settling hazard in the foundation of the rig and also a disposal problem. In some foundations refrigerating equipment must be used to prevent settling.

Permafrost also may act as a trap for oil or even have oil reservoirs within it. The cold temperature adversely affects asphalt-base types particularly and cuts down yields. Production difficulties and costs go up (Fagin, 1947).

Refrigeration and Storage

Natural cold-storage excavations are used widely in areas of permafrost. They are most satisfactory in continuous or discontinuous zones. Permafrost should not be above 30° F.; if it is, extreme care in ventilation and insulation must be used. Properly constructed and ventilated storerooms will keep meat and other products frozen for years. Detailed plans and characteristics required for different cold-storage rooms are described by Chekotillo (1946).

Trafficability

In the Arctic and sub-Arctic most travel overland is done in winter, as muskegs, swamps, and hummocky tundra make summer travel exceedingly difficult (Navy Department, 1948–49; Fagin, 1947). Tracked vehicles or sleds are the only practical types. Wheeled vehicles are unsatisfactory, as most of the area is without roads.

Permafrost aids travel when it is within a few inches of the surface. It permits travel of D8 caterpillar tractors and heavier equipment directly on the permafrost. Sleds, weighing many tons, can be pulled over the permafrost with ease after the vegetal mat has been removed by an angle-bulldozer. Polygonal ground, frost blisters, pingos, and small, deeply incised thaw streams (commonly called "beaded" streams), rivers, and lakes create natural hazards to travel.

In areas of discontinuous and sporadic permafrost, seasonal thaw is commonly 6 to 10 feet deep, and overland travel in summer can be accomplished in many places only with amphibious vehicles such as the weasel or LVT. Foot travel and horse travel are very slow and laborious in many places because of swampy land surfaces and necessity for making numerous detours around sloughs, rivers, and lakes.

Military Operations

Permafrost alters military operations through its effects on construction of airbases, roads, railroads, revetments, buildings, and other engineering projects; through its effects on trafficability, water supply, sewage disposal, excavations, underground storage, camouflage, explosives, planting of mines, and other more indirect ways (Edwards, 1949; Navy Department, 1948–49). Military operations commonly require extreme speed in construction, procuring of water supply, or movement of men and material. Unfortunately it is not always humanly possible to exercise such speed (Fagin, 1947). Large excavations require natural thawing, aided possibly by sprinkling (Huttl, 1948), to proceed ahead of the earth movers. Conversely, seasonal thaw may be so deep as to prevent the movement of heavy equipment over swampy ground until freeze-up. Or, similarly, it may be necessary in a heavy building to steam-jet piles into permafrost and allow them to freeze in place before loading them. These tasks take time, and proper planning is a prerequisite for efficient operation.

Camouflage is a problem on the tundra. Little relief or change in vegetation is available. Tracks of heavy vehicles or paths stand out in marked contrast for years. It is easy to see in aerial photographs foot paths and dog-sled trails abandoned 10 years or more ago.

Mortar and shell fire, land mines, shaped charges, and other explosives undoubtedly respond to changes in the character of permafrost, but no data are available to the author.

FUTURE RESEARCH NEEDED

Throughout the foregoing pages brief reference is made to aspects of permafrost or effects of permafrost on engineering, geologic, biologic, and other scientific problems for which few factual data are available. However in the event that the reader has received the impression that a great deal is known of permafrost, it is pointed out that the science of frozen ground is relatively young and immature. It has lacked a coordinated and comprehensive investigation by geologists, engineers, physicists, botanists, climatologists, and other scientists. It is barely in the beginning of the descriptive stages, and only now is it receiving the world-wide attention it deserves.

As our civilization presses northward, the practical needs of construction, water supply, sewage disposal, trafficability, and other engineering problems must be solved speedily and economically. Our present knowledge is relatively meager, and trial-and-error methods are being used much too frequently. Practical laboratory experiments (Taber, 1930a, b) and controlled field experimental stations, such as that at Fairbanks, Alaska (Jaillite, 1947), are needed in various situations in the permafrost areas. From these stations methods and techniques of construction can be standardized and appropriate steps taken to meet a particular situation. Such laboratories must be supplemented with Arctic research stations such as are found in the Soviet Union where more than 30 natural-science laboratories with permanent facilities and year-around basic studies in all phases of Arctic science are going on. The Arctic Research Laboratory at Barrow (Shelesnyak, 1948) is a start in the right direction. The academic approach must accompany the practical approach if satisfactory solution of the problem is to be found.

To name all the specific topics for future research would make this section unduly long, as no phase of permafrost is well-known. However, the author reiterates that the problems cannot be solved adequately until the phenomena of heat flow in all natural and artificial materials in the earth is understood and correlated with insolation, atmospheric conditions, geothermal gradients, and the complex surface of the earth. Then, possibly, criteria can be set up to evaluate within practical limits the effect of various structures on the dissipating surface of the earth. The complexities of geology (lithology, structure, and texture of soils and rock), hydrology, vegetation, and climate of the Arctic make the solution a formidable task but the research an intriguing problem for all earth scientists.

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Chapter 15

GEOLOGY IN SHORE-CONTROL PROBLEMS

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The development of knowledge of shore processes has been due traditionally to the interest of geologists and others working in related fields. However, in the application of that knowledge to the increasingly important practical problems of shore-control, contributions by geologists have been notable for their absence. This chapter purposes to call the attention of geologists to some of the challenging practical problems encountered by engineers concerned with shore control and the manner in which geologists may contribute to the solution of the problems.

SHORE-CONTROL PROBLEMS

The problems of stabilization and rehabilitation of beach areas are the most widespread of shore-control problems. Stabilization is of high economic significance in resort areas, such as the New Jersey coast or the Miami-Palm Beach coast of Florida, but the significance varies only in degree in the case of individual property owners. In the typical instance, highways, homes, hotels, business establishments, and other structures pertinent to beach utilization in American society are located, during the development period, immediately adjacent to the beach. Little, if any, allowance is made for the possibility of encroachment by the sea (Fig. 1). When erosion of the beach occurs, as it normally does, the structures are endangered or damaged, and the engineer is called in to prevent further erosion and rehabilitate the beach. Both planners, where they have participated in beach developments, and property owners are at fault in such situations for not having provided an adequate marginal area to allow for the inevitable encroachment of the sea. The shore-control engineer is consulted after the patient is ill, in many cases in extremis, and his problem is to plan and construct defenses or works that not only will resist the attack of the sea but also will regain at least a part of the shore already lost. Often the problem is presented as treatment of a limited area, say a few hundred feet of frontage, within a large region of erosion, the re-

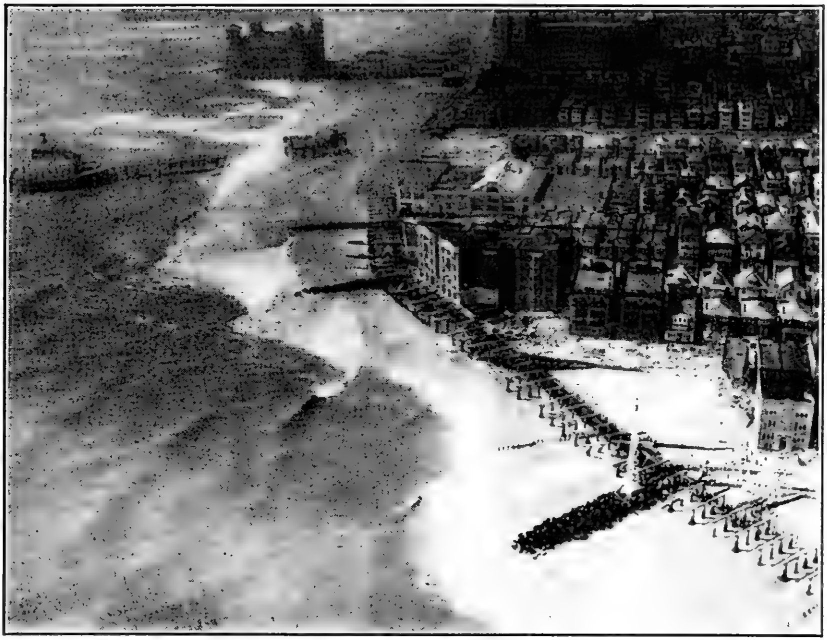

FIG. 1. Atlantic City, New Jersey. The highly vulnerable position of structures built without allowance for an adequate margin for erosion is well illustrated. September 1944. (Photo by U. S. Navy.)

mainder of the region being endangered but the property owners being in economic circumstances precluding any corrective action.

Another typical problem frequently encountered is that arising from the provision of deep navigation channels from the sea or lakes into rivers or inlets. To illustrate this problem we may assume an inlet into a bay. Initially, under natural conditions, the inlet channel might have had a controlling depth of, say, 10 feet, and would have migrated within certain limits. As the channel approached one limit of its migration, a new channel would break out near the opposite limit, with the old channel closing as the new channel improved, the new channel then migrating to repeat the cycle. In the usual case there would be a submerged bar associated with the inlet channel. Now demands are made for a channel of greater depth, say 20 feet, and the stabilization in position of the inlet channel to serve the interests of navigation. The engineer recognizes that the natural conditions represent an equilibrium situation involving, among other factors, the rate of transport of material alongshore and the tidal or flow characteristics of the inlet. Equilibrium will be destroyed by dredging of a chan-

FIG. 2. Cold Spring Harbor, New Jersey. A wide beach has been formed by material trapped by jetties (right). The downdrift beach (left) is starved and subject to serious erosion. April 1940. (Photo by Aero Service Corp.)

nel, and natural forces will tend to re-establish equilibrium, in part at least, by filling the dredged channel. Jetties, or structures parallel to the channel axis and extending from shore seaward to the end of the dredged channel, are usually provided to eliminate refilling of the dredged channel. These structures, however, also inhibit or prevent the natural movement of material alongshore, thus establishing a new regimen which probably will involve starvation of the downdrift beaches due to interruption of the natural littoral supply (Fig. 2). The engineer's problem then is so to design the navigation works as to interfere as little as possible with the natural littoral transport of material, yet protect the navigation channel against filling, and to provide palliative measures for such deleterious effects of the works as may not be avoided.

A third type problem of shore control is associated with harbor-protective works. These works take the form of breakwaters and jetties extending seaward from the shore. Their function is to protect a given water area against wave action, thus providing a shelter for craft.

FIG. 3. Santa Barbara, California. Littoral material impounded by harbor breakwater and passing into harbor. June 1938. (Photo by Beach Erosion Board.)

Unfortunately the structures projecting from the shore act as barriers to the natural movement of material alongshore. The offshore structures, or breakwaters, reduce or destroy wave action, thus eliminating the principal force that causes material transportation. The problem here is to prevent starvation of the downdrift shore, and in some cases to control excessive accretion of material on the updrift side of the harbor. Santa Barbara Harbor, California (Fig. 3) is an excellent illustration of the problem. A dog-leg, or curved, breakwater was built from shore into deep water to provide a sheltered anchorage for small craft. Within a few years the entire updrift area of impoundment of the jetty was filled to capacity, and littoral drift passed into the harbor, shoaling it to such an extent that it became partially unusable. Concurrently, erosion of the downdrift shore occurred, finally extending its effects almost 10 miles downcoast from Santa Barbara.

The evidence at hand indicates that the net results of the action of shore processes over the period of record is an average annual loss of

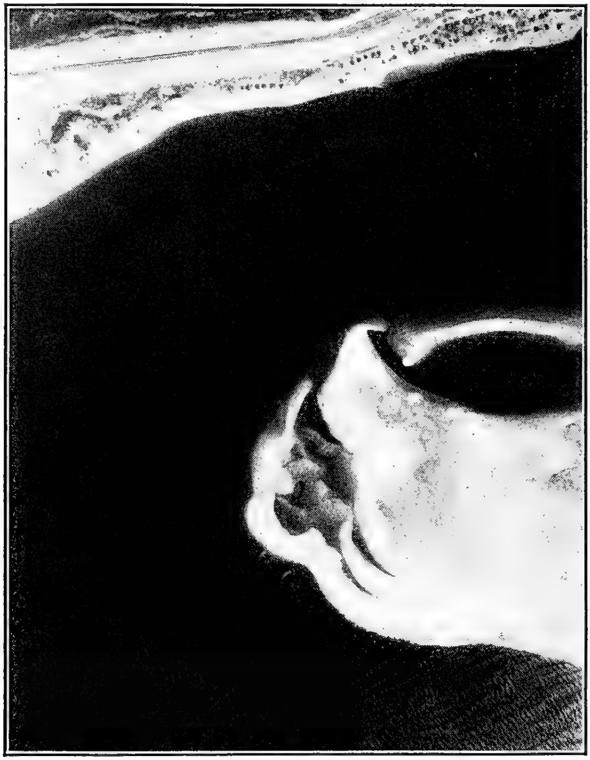

FIG. 4. Fire Island Inlet, New York, before construction of jetty, September 1939. (Photo by Beach Erosion Board.)

land in the United States equivalent to about a 1-foot strip over our entire 52,000 miles of shore line, a loss in land area approximating 6,400 acres per year. In some areas loss is general and excessive, for example, the Chesapeake Bay area, where entire islands have disappeared by erosion within the memory of man, and where the unprotected shores of both developed and agricultural lands are now being lost at rates as high as 15 feet or more per year. In other limited sections land is being gained, as at Fire Island Inlet on the south shore of Long Island (Figs. 4 and 5), where littoral drift is being trapped by a recently constructed jetty.

Shore-line modifications vary widely in scale. The larger changes are those involving considerable physiographic modification, for example, the truncation of headlands and the associated formation and growth of spits and bars; or the very important formation of barrier beaches and lagoons responsible for the present coastal features of New

Fig. 5. Fire Island Inlet, New York, after jetty construction, 1941. (Photo by Beach Erosion Board.)

Jersey and the south shore of Long Island. It is in the study of these large-scale changes that geologists have made their greatest contributions to knowledge of shore processes in the past. The information developed is of great value as background for the solution of practical problems of control, but because of the long-term nature of the phenomena it is of lesser value in study of the relatively short-term problems of control. Shore-control engineers seek and need immediate control methods, effective for perhaps 20 to 50 years, and, justly, have little direct interest in or use for information about processes involving perhaps thousands of years for their consummation. It is in the study of small-scale, short-term shore processes that the need for assistance from geologists is most important.

The economic importance of shore control is largely a function of the development and use of the specific shore area considered. At Atlantic City, New Jersey, the shore-front property has a value of about $200,000,000, and this value is dependent in major part on the maintenance in satisfactory condition of some 10,000 feet of shore. Judged by this standard, each front foot of beach at that locality has a worth of $20,000. Other resort areas have similarly fantastic worth attaching to their limited sea boundary.

The value of beaches is strikingly illustrated by examination of the expenditures made to maintain or retain them. The State of New Jersey has spent $1,000,000 annually for 20 years in protecting its beaches. Harrison County, Mississippi, is spending federal and state funds in excess of $2,000,000 to repair a sea wall and provide beaches for the cities of Biloxi, Gulfport, and Pass Christian.

It is in navigation-shore-control problems that the economic significance of shore control is most striking. The annual reports of the Chief of Engineers, U. S. Army, covering the major portion of such problems, show that each year the federal government alone spends $48,000,000 to remove about 185,000,000 cubic yards of sediment deposited in navigation channels. In addition, millions of dollars damage to downcoast shores is caused by the trapping of these unwanted deposits and their resulting loss from the littoral supply.

It is difficult to assess the total economic significance of shore control to the people of the United States. Perhaps a conservative guess might be of the order of $100,000,000 annually, considering only actual expenditures and damage costs, and disregarding the intangible and difficult to evaluate costs associated with loss of recreational benefits and loss of shore area without immediate resulting damage.

FACTORS INFLUENCING THE PROBLEM

Two concepts are fundamental to the study of shore phenomena. The first is that of the physiographic unit. This unit may be defined as a shore area so limited that the shore phenomena within the area are not affected by the physical conditions in adjacent areas. Analysis of shore problems indicates that, for the purposes of studies directed toward protection or modification of the shore, all important phenomena depend on the material and energy available to the shore. What we seek in a physiographic unit, therefore, is a shore area so defined that the energy and material available within the area are not dependent on adjacent areas. Thus, for example, we may consider an island as a physiographic unit; it is probable that the entire Atlantic coast of New Jersey from Sandy Hook to Cape May is a unit; and on a smaller scale, Monterey and Emerald bays (Fig. 6) in California are units. The physiographic unit defines the boundaries of the area to be studied when considering shore problems.

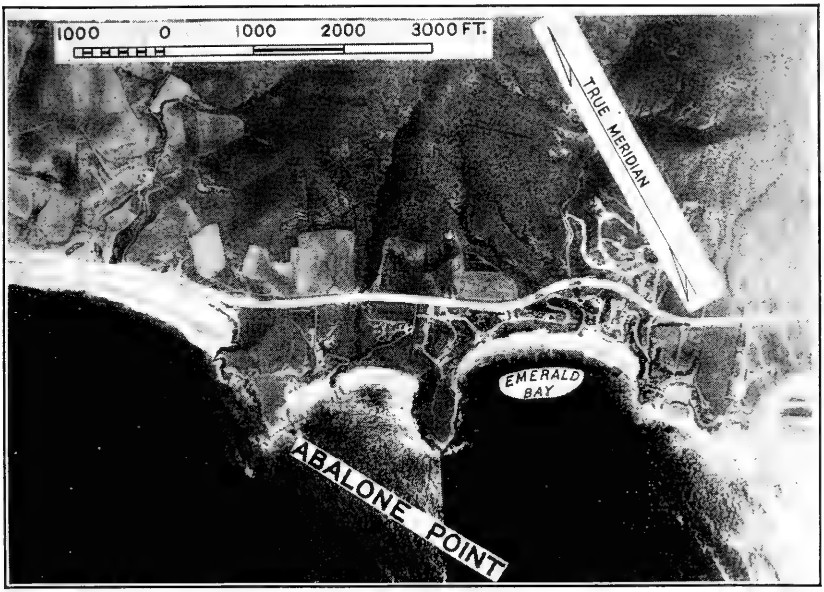

Fig. 6. Emerald Bay, California. A physiographic unit.

The second basic concept is that of material-energy balance within the physiographic unit. Material balance concedes equality between the quantity of material supplied to and that lost from a shore area. Obviously a time factor must be introduced which requires that the volume of material considered be thought of as a rate of supply or loss. We are concerned chiefly with material balances pertaining to days, seasons, years, and storm durations. Since material is moved into and away from any given beach or shore section only by the application of forces, we must think also of rates of doing work, or energy.

Let us examine briefly the factors involved in material balance. If we assume some hypothetical shore stretch and consider the material situation therein, we find that formulation of a complete balance requires knowledge of (1) the rates of littoral drift to and from the area; (2) the rates of supply and loss from and to the adjacent sea bottom; (3) the rates of supply and loss from and to the adjacent land, including specifically dune areas and other marginal-land features; (4) the rate of supply of material contributed by drainage features. Unfortunately it is not possible, in the present state of the science, to evaluate these factors in other than a qualitative fashion.

Comparative study can indicate the probable relative importance of each of the factors, but only rarely are quantitative data available. In many areas only cursory examination is required to establish the littoral drift as the most important item, for example, along the New Jersey coast; whereas other areas are very complicated, for example, the Monterey Bay, California, coast where a submarine canyon and large supplies of material brought to the coast by streams greatly influence the coastal regimen and probably completely dominate the littoral phenomena.

Littoral drift is now evaluated by the amount of material trapped by shore structures, either natural or man-made, and from knowledge of the rate of depletion of sources of supply, for example, eroding cliffs or headlands.

Estimation of the material volume derived from or lost to the adjacent sea bottom is unsatisfactory at present. Experiments are in progress at reduced scale in the laboratory which give promise of confirming some conclusions reached from theoretical considerations regarding material transportation on the sea bottom. However, there is little, if any, evidence of a conclusive nature with respect to this phenomenon in nature.

The quantity of material derived from or lost to the land is now evaluated with fair accuracy by comparative study of the topography of the area at various times, coupled with knowledge of the character of the land and shore material.

The determination of the volume of material supplied to a shore area by streams, gully washes, or other drainage features is facilitated by knowledge of the suspended and bed load carried by the flow. Sometimes this information can be gained from study of the stream mouth delta, more easily from records of the rate of silting, or filling, of the stream upstream from the mouth. The wide variation of material load carried, between flood and normal stages, must be kept in mind.

Wave action is the primary source of energy at the shore. Its importance is overriding everywhere on the open coast and is not seriously diminished even in the immediate vicinity of large tidal entrances. The waves of concern are the characteristic progressive oscillatory surface waves so familiar to all, the long-period swell not usually so apparent, and the very long "tidal" waves, or tsunamis, of infrequent occurrence.

The surface waves and swell result from atmospheric disturbances over the ocean and are propagated over long distances with very slowly diminishing intensity. As a general rule these waves are always present on the ocean to a greater or lesser degree, from the days of dead calm when only very long and low remnants of swell from far-distant storms exist, to the days of violence when waves are being generated by a storm on or near the coast. Their action is unceasing and of an almost unbelievable magnitude. It is believed at present that waves derive their energy entirely from the wind systems to which they are subject, and that this energy is dissipated, except for a negligible fraction lost to internal friction, on the shores ultimately attacked by the waves. "Tidal" waves or tsunamis constitute a special case; because of their infrequent occurrence in highly violent form, they will not be discussed here, although they can by no means be neglected.

Theoretical studies, confirmed by laboratory experimentation and some observations in nature, show that surface waves involve motion of the water only to a depth equal to about one-half the length of the wave from crest to crest. The water moves in circular or elliptical orbits or paths which do not quite close; that is, there is a small excess forward motion associated with the passage of each wave, and this motion has been called the mass transport of the wave. Its magnitude is only a few percent of the actual orbital velocities, which range from 0 to a frequently attained maximum in excess of 6 feet per second. The velocity at the bottom varies with the depth of water, the wave length or period, and the wave height; it is the velocity most effective in causing erosion and transportation of material. As a wave moves into shallow water, the bottom velocities due to the wave increase by reason of decreasing depth but the wave energy is not greatly changed. Finally the wave breaks in surf, dissipating most of its energy in a highly turbulent, violently churning area, with the remainder dissipated during the rush of the wave up the beach. It is commonly held that the most active erosion and transportation zone is the area involved in the break of the wave and its uprush on the beach.

A fair evaluation of the energy available from the waves can be made if knowledge of the wave periods and heights is available, because it is known that the wave energy is proportional to the product of the period squared (T^2) and the height squared (H^2):

$$E \sim T^2H^2$$

If in addition information on the direction of approach to the shore of the waves is available, it is possible to formulate a time distribution of wave energy with respect to direction of application of the energy.

From the engineer's point of view the adequate solution of shore-control problems is contingent on accurate knowledge of the following factors: (1) the sources and character of the beach material; (2) the rates of supply and loss of material to and from the problem area; (3) the manner of movement of material from the source to the beach and from the beach to other areas.

It is immediately apparent that, if answers to these questions can be obtained, the physical conditions that cause the problem situation will be defined. This is the definition of the problem. It has been the experience of investigators in this field that there are usually unique definitions of the problems; each problem is separate and distinct, thus making the solution of such problems by analogy an unsatisfactory method. There has been a tendency to practice solution by analogy, which still continues to some extent but which is on the decline as more and more knowledge of the problem is developed.

The physiographic unit is of value in determining the source and character of the beach material, particularly if the surficial geology of the area has been adequately studied. The material-energy balance of the unit, and specifically of that portion of the unit requiring control, greatly facilitates the consideration of the last two factors.

Frequently the definition of the physical conditions at the site by consideration and study of the above factors will suggest the type, and sometimes the detail, of the control to be employed. However, to arrive at a rigorous engineering solution the problem is analyzed further.

The analysis reduces to consideration of the following factors: (1) the feasible methods of modifying rates of supply and loss of material to achieve the desired results, and the effects of such modification; (2) the design requirements of the feasible methods of modifying supply and loss rates; (3) the economic cost of each of the feasible methods of modifying rates of supply and loss.

COLLABORATION BETWEEN GEOLOGISTS AND ENGINEERS

Geology can help engineering in connection with all but the last factor, but it must, to be of maximum value, focus attention on the dynamic aspects and significance of its findings. The average engineer who needs the information has little, if any, means of translating classical geologic information into a form he can use. A geologist in-forming an engineer that a beach deposit is recent in the geological sense, and derived from Quaternary deposits, is not helping the engineer. He will have made a major contribution if instead he can say that the beach deposit was probably made in the last half-century and that the material was derived from sandstone in such and such locality by erosion and stream transportation to the beach. The possibilities of interpretation of geologic information with a view to defining the dynamics of the environment have been realized but slightly. In this field they are particularly rich.

The geologist is eminently qualified to furnish basic data needed for shore control. Particularly is this true with respect to the definition of physiographic units and the determination of the source and character of littoral material. The engineer must contribute to the geologist knowledge of the forces acting and the nature of their distribution in time and space. Close collaboration between the two professions in the study of these problems will produce results of high economic significance with a minimum of effort. Almost all that is required is a wedding of the static and dynamic analyses now available.

Another area of collaboration that promises useful results quickly lies in study of the sources and transportation phenomena of material movement. Geologists already are informed about many of the details of the derivation of beach material from source rocks and the resulting characters of the material. Some of the gross details of transportation effects on the materials, for example, selective transportation and rounding, have been explored, chiefly by geologists, but much remains that can be done. The engineer can provide knowledge of some of the dynamic situations to which the material has been subjected, for example, the mechanisms of bed-load movement and the rate of mass movement of material in various types of watercourses. Here again the study of cause and effect with particular reference to the dynamic processes involved should produce immediately useful relations of value to both the geologist and engineer. The establishment of verified relations between material characteristics (including both discrete particles and aggregations of particles) and the dynamic processes in which the material has participated should open possibilities for a much better understanding of the details of transportation and deposition of sediments.

Engineers and geologists could well consider collaboration with a view to detailed study of the energy-material relations controlling physiographic changes at the shore. Engineers can supply much information on wave energy, its distribution along the shore and modification with changes in the shore conditions, which, coupled with geological knowledge of the materials present to be acted upon, might well lead to quantitative descriptions of physiographic processes.

Collaboration can probably be effected best by liaison between individuals and collaborative research. The field is too narrow and the specialization required too high to permit a more general approach. Some instances of combined application of engineering and geological knowledge, notably by W. C. Krumbein in the study of the details of littoral movement, have led to highly useful concepts that explain formerly complex situations.

FUTURE RESEARCH

In our present state of knowledge needed future research can be specified only in general terms. It can be stated that wide opportunities exist for research, and any discussion of needed research will certainly encompass only a part of the wide variety of problems that may exist.

One of the first problems to be studied as a concurrent geological-engineering problem is that of the definition of physiographic units for shore-study purposes. The problem involves, among others, determination of material sources and the transportation sequence from the source to the shore, with considerable attention to be devoted to the volume and time scales of the phenomena; determination of the limits of littoral transportation, both eolian and submarine; and consideration of the energy situation.

A second problem of prime importance in the study of many shore processes is the relation between shore-material characteristics and the dynamic processes of transportation to which the material has been subjected. Shore studies are concerned with the behavior of a population of particles in which the behavior of the population is conditioned by, and may be chiefly dependent on, the characteristics of the individual particles. The possibility exists that modification of one small fraction of the particles may change appreciably the behavior characteristics of the population. For example, it is known that the admixture of small amounts of clay in sand greatly increases the velocity required to erode the sand. More adequate definition of the erodibility and transportability of beach materials in terms of their particle characteristics is required. Determination of the erosion susceptibility of beach materials when subjected to the oscillatory velocity fields of wave action is a virgin territory, as is the problem of transportation on the bottom or in suspension under the same conditions.

There is some justification for thorough study of the details of selective transportation of shore material, with particular reference to the disposition of material. Closely related to this problem is the question of thickness of beach and near-shore deposits and their stratification as indicators of the past history of the beach.

In these suggested research problems as well as in others, the usefulness of tracers having the same dynamic characteristics as the materials under study is apparent. There is some evidence that adequate knowledge of the petrography of shore and source materials would make possible the use of some fractions of the native materials as tracers, thus greatly simplifying some of the technical phases of the studies.

It must be apparent that there are great deficiencies in our knowledge of even some of the less complicated phenomena of shore-line behavior. It is believed that future developments in shore study and control are contingent principally on fundamental research in materials, the transportation of materials, and methods of modifying the material-energy balance of an area. In the field we are concerned with, as in many other technical fields, there is presently a serious, almost critical shortage of basic information. Without such information, the technical man finds it impossible to advance applied research. In this field engineers have progressed as far as they have mainly on fundamental research in other fields, notably geology, hydraulics, mathematics, and physics. Our greatest need is for work on shore materials and the transportation of materials under maritime conditions. Available knowledge of unidirectional transportation of material in streams is of only partial value to us in our problem of multidirectional flow under periodically varying forces. We must know more about the details of material derivation from source rocks, the degradational processes of derivation and transportation, the possibilities of metamorphosis of constituent particles and populations of particles. It is essential to know the details of littoral movement of materials, the relationships of energy to material movement, the features of energy transfer and dissipation in the coastal environment, the requirements for modification of the material-energy balance, and even how to compute an accurate, quantitative material-energy balance.

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Chapter 16

SEDIMENTATION IN HARBORS

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This chapter will be devoted to a brief discussion of the engineering and, to some extent, the economic aspects of sedimentation in harbors. Many of the statements herein will be recognized as applicable to navigation channels in general as well as to harbor channels and anchorages.

In most harbors, man has artificially increased the depth of water over that normally existing at the locality in order to accommodate the movement, anchoring, and berthing of vessels. The tendency for natural forces to restore the normally existing depths is the crux of the sedimentation problem.

For the purposes of this discussion, sediment is considered to be any detritus, from gravel to clay particles, which moves into and is deposited in commercial harbors by natural means, such as stream flow, tidal flow, or wave action. Harbors are found along the open coast, in the tidal rivers and bays connected with the ocean, along the fresh-water rivers, and along the larger interior lakes. The causes and magnitude of shoaling in these different types of harbors are varied. Correspondingly, the attempted cures, both successful and unsuccessful, have varied. Generally speaking, all have been expensive. Harbors have been classified as river-channel harbors, off-river harbors, fall-line harbors, tidal-channel harbors, off-channel tidal harbors, and shore-line harbors; the terms will be explained in turn below.

RIVER-CHANNEL HARBORS

Many fresh-water non-tidal riverside harbors are developed in the river channel proper. Examples of such harbor developments are: Baton Rouge, Louisiana; St. Louis, Missouri; Pittsburgh, Pennsylvania; Sacramento, California; Mainz (on the Rhine), Germany; Budapest (on the Danube), Hungary; and Chungking (on the Yangtze), China. For the most part, fresh-water streams keep the silts and clays moving, and the sedimentation problem becomes one of sand. Such harbor sites are usually selected initially where a deep pool exists in the bottom contours of the river rather than in one of the crossing or bar areas. However, the meandering tendencies of the river beds, the shifting in the bar locations with varying flows in the river, dredging to increase navigable depth, or attempts to expand the harbor beyond the limits of the pool frequently result in the creation of a shoaling problem in the harbor.

Solutions of the problem have been for the most part confined to:

(1) Dredging to remove the sediment.

(2) Partially enclosing the harbor area with training walls and dikes. This sometimes results in the silting of the harbor by the deposit of silt and clay in the dead-water area created. The channel from the river to the harbor also continues to be subject to shoaling.

(3) Use of training walls to divert sand-laden bottom waters past the harbor and allowing only the sand-free top water to enter the harbor. This procedure can have the same results as (2) unless care is taken to maintain sufficient flow to flush the harbor.

(4) Diverting the river to another course to by-pass the harbor. This in effect makes the harbor an off-channel harbor, which is discussed below.

(5) Construction of locks and dams in the river channel, thereby increasing depths in the harbor area.

In order to avoid, lessen, or eliminate shoaling in harbors of this type, it would appear that a better understanding is needed of the following: (*a*) the laws governing the meandering of rivers; (*b*) the laws governing the movement of sand by flowing waters, including a study of the action when the flow is bifurcated by a dike or training wall; (*c*) the laws governing the intermixing of river and harbor waters, which results in the silting action described in (2) above; (*d*) the laws relating to non-silting velocities as related to (3) above.

OFF-RIVER HARBORS

Many river harbors are essentially landlocked in that the harbor is not in the river channel proper and is connected with the channel only by the navigation access channel. Such harbors are usually stagnant-water harbors except for small local stream flow, and the interchange of water between the river and the harbor. Examples of off-river harbors are Greenville, Mississippi, and Freeport, Texas.

These off-channel harbors generally have little difficulty with sand and gravel, though the channel from the river to the harbor may be subject to severe shoaling. Such harbors, however, do have difficulty with silt and clay brought in by the interchange of the waters in the harbor and the river. This silt and clay may settle in both the entrance channel and the harbor proper.

Solutions to the problems involved in the development and maintenance of such harbors and entrance channels have for the most part been:

(1) Dredging to remove shoal material from entrance channel and harbor proper.

(2) Construction of training walls and dikes at river entrance to decrease rate of shoaling in entrance channel.

(3) Construction of locks or floodgates that will decrease the interchange of water between the river and the harbor during time of turbid flow in the river.

Advances in the knowledge of the following phenomena would be helpful in the development and maintenance of such harbors: (*a*) characteristics of movement of bed load in a flowing stream to enable better selection of entrance channel sites and design of protective work at the river entrance; (*b*) intermingling or exchange of silt-laden river waters with less turbid waters in the harbor as a step toward developing means to lessen the rate of interchange.

FALL-LINE HARBORS

Economic considerations have frequently brought about the development of harbors at the transition in a river course from a relatively turbulent mountain river to a more or less placid tidal estuary. This transition point, or fall line, is very well marked in certain areas, particularly along the eastern seaboard of the United States, where the Appalachian foothills meet the tidewater area. Examples of fall-line harbors developed in such areas are: Troy, New York; Trenton, New Jersey; Washington, D. C.; and Richmond, Virginia.

These fall-line harbors are generally troubled with shoaling due to sand and gravel, or even small boulders, brought down by the relatively high-velocity flood flows in the mountainous section into the harbor area, where the increased stream cross section results in much less velocity with an accompanying deposit of shoal material in the harbor. In some areas the conditions are such that the tidal flow in the harbor area, supplemented by normal river flow, would in time flush out the excess material moved in by the river floods; however, this is of little real benefit as the excess shoals in an active harbor cannot be tolerated even for short periods. As a result, frequent and often expensive dredging has to be resorted to in order to maintain usable depths.

Solutions to problems at fall-line harbors have been:

(1) Dredging as necessary to remove accumulated shoal.

(2) Use of training walls and dikes in an attempt to divert mass of shoal material away from the harbor proper. This, of course, can result in the shoal forming in the ship channel connecting the harbor with the sea.

(3) Creation of off-channel harbors. Such construction is expensive and, of course, does not eliminate the deposit of the shoal material in the ship-channel proper; it generally results in the same problem described above for off-channel river harbors.

It would appear that the most useful information leading to solutions of this type of problem would be that dealing with a study of competence of flow to move sand and gravel. This information might conceivably lead to the design of training works or channel alterations that would spread the shoal over a greater distance, with accompanying greater navigation depths, thereby giving the tidal flow plus normal fresh-water flow a chance to flush the shoal material down the river without excessive shoaling.

CHANNEL HARBORS IN TIDAL ESTUARIES

Most of our larger harbors are located on tidal estuaries, the term estuaries being taken in its broadest sense to include tidal rivers, bays, and lagoons. In most harbors in tidal estuaries, a sizable tidal prism moves through the harbor as a result of the flood and ebb of the tide filling the tidewater area farther up the estuary. Examples of such harbors are numerous, including New York, New York; Philadelphia, Pennsylvania; Savannah, Georgia; Jacksonville, Florida; Galveston, Texas; Mare Island Straits, California; Canton (on the Yangtze), China; St. Nazaire (on the Loire), France; Antwerp (on the Scheld), Belgium; and London (on the Thames), England.

In some of these harbors the velocities of tidal flow—particularly when reinforced by river flood flows—are competent to move sand, and the problem of sand shoaling is of concern. In general, however, the problem is one of shoaling from silt and clay. Several factors serve to augment the tendency to shoal by silt and clay sedimentation: among these are (1) the slack water periods between successive tides, during which slack water periods the water has no turbulence acting to keep the suspended silt and clay in suspension; (2) the intermixing of the silt-laden fresh water with the salt water brought into the estuary by tidal currents and density currents, this intermixing causing flocculation of the suspended material and greatly accelerating its tendency to settle to the bottom.

Attempts to overcome the problems connected with sand shoaling have been similar to those for river-channel harbors described earlier in this chapter. For shoaling due to silt and clay sedimentation, however, other solutions have been attempted, among them:

(1) Increasing the tidal prism passing through the harbor area in an attempt to create sufficient velocities to flush out the harbor channel. This increase in tidal prism may be effected in various degrees by improving the hydraulic characteristics of the estuary channel above and below the harbor, or by creating a greater tidewater area above the harbor.

(2) Giving the ebb flow a dominance over the flood flow in the harbor by a suitable arrangement of training walls or one-way tide gates. The purpose of giving the ebb flow the dominance is to insure the movement of shoal material through the harbor and on downstream. This method is conceivably adaptable to problems of both sand shoaling or shoaling from silt and clay.

(3) Decreasing the tidal prism passing through the harbor to a minimum, thereby keeping the amount of potential shoal material entering the harbor to a minimum. This entails creating what is essentially an off-channel harbor, as discussed below.

Contributions to the following fields would probably serve to assist in the solution of problems dealing with harbors of this type:

(1) A study of factors affecting the rate of settling of suspended silt and clay in harbor areas, particularly with reference to flocculation in the presence of sea water.

(2) Competence of flowing water to flush sand deposits and silt and clay deposits in various stages of compaction out of harbor areas.

(3) Improvements in tidal theory to enable more reliable computations of effect of changes in tidal regime on resulting tidal prism.

(4) A better definition of the laws of intermixing of sea water and fresh water and of the action of density currents.

OFF-CHANNEL HARBORS IN TIDAL ESTUARIES

In an attempt to avoid the high rates of shoaling due to excessive movement of silt-laden tidal waters through the harbor area, many off-channel harbors have been created in tidal estuaries. Examples of such off-channel harbors are: Washington Channel Harbor, Washington, D. C.; Texas City, Texas; Houston, Texas; London, England (in part).

Generally the off-channel harbor is subject to shoaling from suspended silt and clay brought into the harbor by the interchange of tidal waters between the harbor and the estuary. Moreover, the problem of the shoaling of the channel connecting the off-shore channel with the estuary remains a problem.

Improvements to such off-channel harbors have been attempted along the same lines as for off-channel river harbors, principally:

(1) Dredging to remove excess shoaling.

(2) Use of training works to protect entrance channel (Texas City, Texas).

(3) Locks to reduce interchange of water between harbor and estuary (London, England, in part). It is to be noted that such locks are at times designed primarily to maintain a constant water level in the harbor where the tidal range is excessive.

It would appear that investigations of the general types described above for channel harbors in estuaries would possibly be the most useful in this type of problem also. An evaluation of the factors governing the interchange of water between the harbor area and the estuary would also be very helpful.

SHORE-LINE HARBORS

Shore-line harbors are intended to include those harbors fronting directly on the open shore of the oceans, bays, or large lakes and having relatively small tidal flow or fresh-water flow from the tributary watershed. These harbors are generally protected from wave action by some natural feature or man-made structures. Notable examples of such harbors are found in the Great Lakes ports such as Chicago, Milwaukee, and Duluth. Both Chicago and Milwaukee rely on man-made structures for protection from lake waves, whereas the main protection at Duluth is afforded by a natural sand barrier. Other examples of shore-line harbors are San Pedro, Santa Barbara, and Port Hueneme, California; Leixoes, Portugal; Algiers, Algeria; and Hong Kong, China. Sedimentation in such shore-line harbors results principally from the littoral drift of beach material due to wave action and alongshore currents or, at times, from detritus brought into the harbor by the fresh-water streams emptying directly into the harbor.

Corrective measures in the improvement of shore-line harbors have been confined generally to:

(1) Dredging to remove the excess shoal.

(2) Construction of breakwaters and jetties to protect the harbor from either wave action and shoaling from littoral drift or both (Port Hueneme, California).

(3) Construction of detached (island) harbors completely separated from shore to allow normal movement of littoral drift along the shore line with bridges provided between the harbor and the mainland. The harbors of Arnager and Snogeback on the Danish island of Bornholm in the Baltic Sea are examples of island harbors.

(4) Improvements in tributary watershed that decrease bed load carried by stream and thereby decrease water-borne detritus deposited in harbor by tributary streams (Los Angeles, California).

(5) Diversion of tributary flow away from harbor area (Mission Bay, California).

Studies leading to a clearer understanding of the character and magnitude of the movement of littoral drift under the influence of wave action and alongshore currents would be of great immediate benefit in the correction of shoaling in shore-line harbors. To a lesser degree, investigations leading to more successful erosion control in the tributary watershed would be of benefit in the correction of shoaling in this class of harbors.

SUMMARY

For the purposes of this chapter, harbors have been divided into five types, and the sedimentation problems generally encountered in each type have been described. Means presently employed to overcome or mitigate the shoaling have also been listed together with a statement of the short-comings of these various methods. It was pointed out that rewarding contributions toward harbor improvement could probably be made by investigations leading to the following:

(1) A better definition of the relation between stream flow and the movement of sand carried as bed load by the stream. This would include a definition of both the rate of sand movement and the path of sand movement along the stream bed. Such information would form the basis of a more rational design of dikes and training walls as applied to harbor design, particularly of channel-type harbors.

(2) A study of the capacity of flowing water to flush accumulated silt and clay shoal material out of harbor areas before such materials have had an opportunity to consolidate. This study would prove valuable in the improvement of channel harbors subject to shoaling by silt and clay deposit wherein currents, either fresh-water or tidal, are periodically present to flush the harbor.

(3) An evaluation of the factors governing the interchange of waters between the main channel flow of a stream or estuary and the waters of a contiguous off-channel harbor. This information would be particularly valuable in the design of off-channel harbor improvements where shoaling is due to silt and clay moving in from the parent stream.

(4) A clearer understanding of the movement of littoral drift under the impulsion of waves and alongshore currents. Such a study should include an evaluation of the rate of drift in various depths under various natural conditions. This information would be particularly useful in the design and improvement of shore-line harbors.

Other investigations that would be of value are mentioned in the body of this chapter; however, the above four fields of investigation are believed to be of particular promise. Improvements in the equipment and technique of dredging would be of obvious value, but this subject is somewhat outside the scope of this discussion. The large yearly expenditures devoted to removal of shoaling in harbors in this country alone would appear to justify considerable effort toward the solution of the various sedimentation problems discussed herein.

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CHAPTER 17

CONTRIBUTION OF MODEL ANALYSIS TO THE SOLUTION OF SHOALING PROBLEMS

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INTRODUCTION

Throughout the ages, man has sought persistently to resolve the physical laws that govern the natural forces affecting his environment. The accumulated thinking and experiments of many generations have provided an impressive fund of exact and useful knowledge. Yet the present knowledge of many fundamental processes is inexact or incomplete, and must be supported by further research and experiment before it can safely be applied to engineering practice. Many problems inherent in sedimentation, or the movement of earth materials by flowing water, would seem to fall within that category. The scope of questions treated in this symposium—by the many professional interests represented—should serve at once to emphasize that the problems and damages resulting from uncontrolled sedimentation are matters that occupy a wide field of interest and are of pressing importance to the national economy. It is striking, then, that a question so significantly related to the utilization and development of major natural resources should be so little understood.

The Corps of Engineers is responsible for the development and maintenance of the navigable waterways and harbors of the nation, a vast interconnected system that now supports a waterborne commerce estimated at more than 600,000,000 tons annually. Wherever the processes of sedimentation reduce the project depths, or tend as a secondary effect to shift channel locations, the Corps of Engineers is immediately confronted with a serious problem. The importance of this problem is emphasized by the tremendous cost of maintenance dredging, an operation that has involved during the past 7 years the removal of approximately 185,000,000 cubic yards of accumulated sediment each year at an annual cost of almost $50,000,000. In order to reduce the scale of this public loss, the Corps of Engineers is vitally interested in diminishing or preventing the sedimentation, or shoaling, of navigation channels. And to further this objective they have brought to bear on the problem in recent years the coordinated resources of the best available in theory, experiment, and practical design.

Laboratory experiment has contributed materially to the success of the undertaking by providing, with the small-scale hydraulic model, decisive information that cannot be derived either from existing theory or from the precedent of past experience. The work of the Waterways Experiment Station in this particular respect has been devoted mainly to hydraulic-model analysis of specific sedimentation problems, for purposes of devising improvements that might eliminate excessive shoaling in the given problem areas. The urgency that usually attends empirical solution of the individual problem has not permitted protracted research of a fundamental nature; nor can the results of a given study be regarded as having universal application. Nevertheless, the experimental program over the course of time has resulted in the development of laboratory procedures and techniques that have proved encouragingly successful for the solution of many perplexing types of sedimentation problems in navigation channels. As a coincidental benefit, the fundamental knowledge of basic processes has been expanded.

The types of problems are as many and diverse, perhaps, as their geographic locations or the intricacies of their natural causes. Also, because of inherently overlapping features, they cannot sensibly be segregated according to any strict classification founded on either their basic characteristics or the techniques employed for their solutions. It is not within the scope of this chapter, however, to discuss all of them; nor is it intended here to treat the theoretical principles of model analysis. It is intended, rather, to describe briefly certain problems that are typical, and to demonstrate by specific examples the experimental techniques applied to their solution. By inference, the scope of this field of research, and its advantages, can then be defined.

PRYORS ISLAND REACH, OHIO RIVER

A problem quite frequently encountered is that of shoaling caused by bed-load movement in an open river with relatively stable banks.

To illustrate the investigation of this type of problem by model analysis, the study of Pryors Island Reach of the Ohio River has been selected as an example.

The low-water channel of Pryors Island Reach (Fig. 1) follows a characteristic series of bends and crossings interrupted at points by island or towhead formations. The maintenance of a 9-foot project depth through this reach was seriously complicated by heavy shoaling at three critical sections: from the head of Pryors Island to the foot

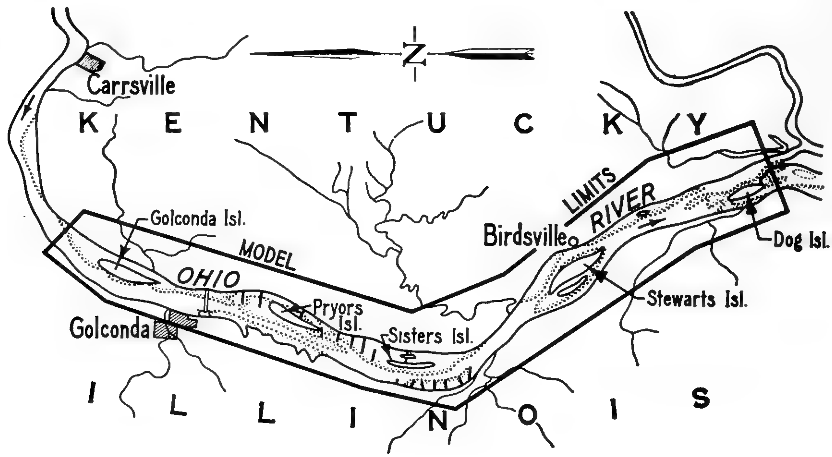

FIG. 1. Location map, Pryors Island Reach model study.

of Sisters Island; just above Stewarts Island; and at Old Maids Crossing just above Dog Island. The purpose of the model study was to develop plans for realignment and dike construction to make the channel self-maintaining.

The basic requirement of a model designed for such purposes is that it reproduce accurately the bed-load movement of the prototype system under similar hydraulic conditions. To achieve this end the bed of the model is constructed of sand, crushed coal, haydite, or other movable material, and hydraulic forces are adjusted until the model will reproduce, within specific time intervals, the changes in bed configuration that are known to have occurred in nature.

The Pryors Island model reproduced a 15-mile length of river, as shown by Fig. 1, to the linear scale ratios of 1:600 horizontally and 1:150 vertically. Banks and overbank areas were molded in concrete to prototype configurations. The stream bed was of crushed coal, molded to prototype contours by means of removable templets. Provisions were made for reproducing any desired discharge hydrograph and for securing proper flow lines through the model. Operation of the model was divided into two distinct phases: (1) adjustment of the model and verification of its accuracy; (2) development and testing of improvement plans for solution of the shoaling problem.

The verification of a movable-bed model is a highly important phase of such a study, inasmuch as the validity of model indications, when transposed to the prototype, rests entirely on this procedure. The time, slope, and other scale relationships necessary to insure proper model bed-load movement are determined largely by the transportability of the available and usable bed materials and cannot be closely established by mathematical means. Hence the model verification, which might be termed an empirical determination of scale relationships, must be depended on to establish the reliability of model data. Verification of the Pryors Island model consisted of a series of tests during which the time scale, slope, bed load, and roughness were progressively adjusted by trial and error until the model would reproduce accurately the hydrographic changes that were known to have occurred in the river between two surveys made 5 years apart. This was accomplished by molding the movable bed to the configuration shown by the earlier survey and then reproducing in the model the sequence of stages and discharges that occurred in the river during the 5-year period, all artificial changes, such as dike construction and dredging, being reproduced in chronological order. The model verification was considered satisfactory when a survey of the movable bed, made at the end of this operation, showed the bed configuration to be an accurate reproduction of river conditions shown by the later survey. It could then be assumed that any changes brought about by training works tested in the model would be a true indication of what might be expected in the prototype if similar works were installed. The model verification fixed the procedure for all subsequent tests of possible improvement plans, and this procedure was followed exactly during all tests. Thus the results of all tests were directly comparable with one another.

The river survey of 1930 (Fig. 2) shows the condition of the river before the adoption of effective remedial works and reveals intermittent shoals from above Pryors Island to below Sisters Island, a shoal above Stewarts Island, and a dangerous crossing above Dog Island. Twenty different plans or modifications, generally involving channel realignment and the construction of stone spur dikes, were tested in the model to arrive at one that would alleviate the shoaling problem in these areas. Figure 3 shows the recommended plan of improvement which was developed in the model. According to this plan, the

Pryors Island and Sisters Island back channels were more effectively diked, and the existing dikes between these islands were raised and extended. The channel opposite Pryors Island was shifted from the

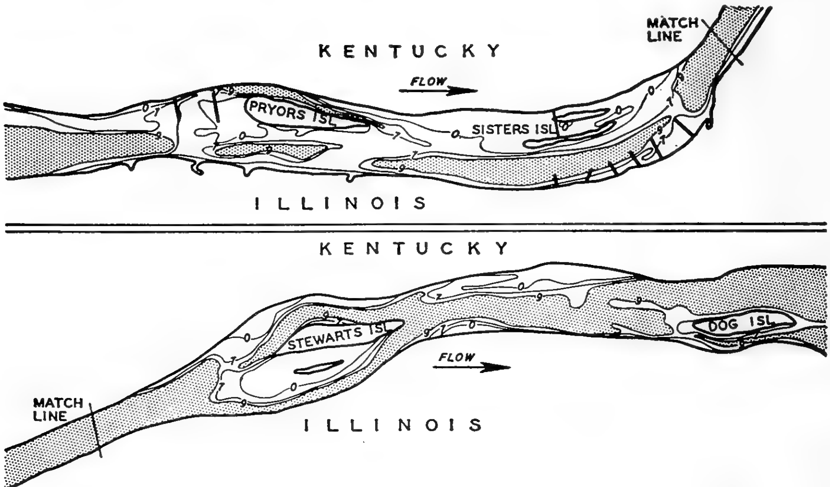

FIG. 2. River survey of 1930, Pryors Island Reach model study.

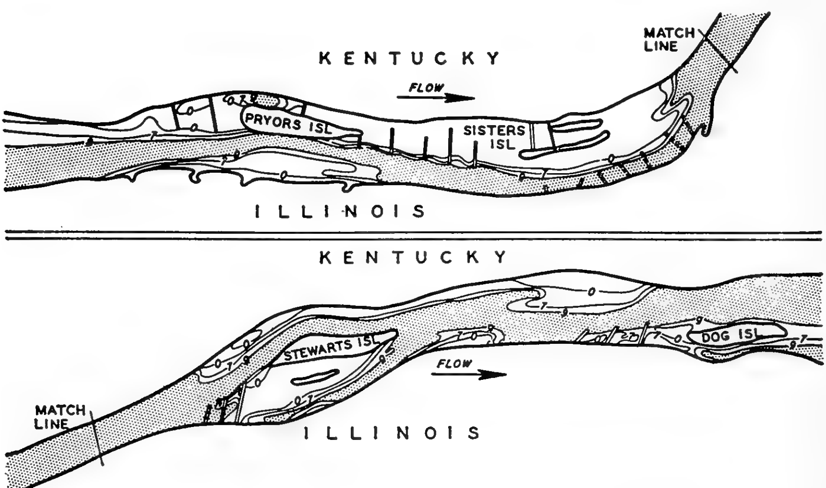

FIG. 3. Recommended plan, Pryors Island Reach model study.

right bank to the left by dredging to a 12-foot depth at the beginning of the test. The seven spur dikes opposite Sisters Island were completely removed. A group of spur dikes was constructed above Stewarts Island and another group above Dog Island. No dredging was done in the model except during the first of the 7 years reproduced in this test, yet a 9-foot navigable channel through the entire reach was open at the end of the test and the bed had reached a stable condition.

DEEPWATER POINT RANGE, DELAWARE RIVER

A second troublesome problem is that caused by the deposition of suspended silt in a tidal stream and, to a lesser extent, by the movement of deposited silt along the bed of the stream. As an example

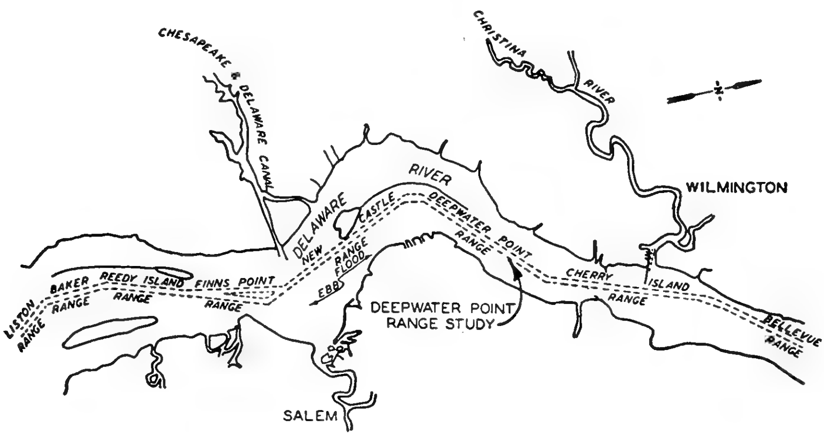

FIG. 4. Deepwater Point Range model study.

of the investigation of this type problem on a hydraulic model, the study of Deepwater Point Range of the Delaware River has been selected.

Deepwater Point Range (Fig. 4) is approximately 4.5 miles long and 800 feet wide with a project depth of 40 feet. At the time of the model study the range shoaled at an average rate of approximately 2,800,000 cubic yards annually, requiring almost continuous dredging to maintain project depth. According to extensive studies, the heavy shoaling was due to lack of parallelism between the tidal currents and the navigation channel. It was expected that the remedy would be found either in realigning the ship channel to conform more closely to the tidal currents or in training the currents into an alignment coinciding with the existing ship channel. It was required of the model used to investigate this problem that it reproduce not only the deposition, distribution, and movement of suspended silt, but that it also take account of the changing levels and reversing currents of the tidal flow (plus the contributions of any fresh-water tributaries).

The model used for this study reproduced that portion of the Delaware River between Artificial Island on the downstream end and Bellevue on the upstream end, plus the tidal reaches of Christina River and Brandywine Creek and about 3 miles of the Chesapeake and Delaware Canal. The model was of the fixed-bed type, molded throughout in concrete to scale ratios of 1:800 horizontally and 1:80 vertically. Tides were reproduced by the movement at either end of the model of gates automatically controlled by an electromechanical system designed for that purpose; the roughness of the model channel was so adjusted that the tides and current velocities and directions were reproduced accurately throughout. Shoaling was reproduced by injecting into the model measured volumes of a mixture of water and finely ground gilsonite, a lightweight bituminous material (specific gravity 1.035) which was found to have characteristics most suitable for purposes of the model. The shoaling material was injected into the model upstream from the problem area during the ebb-tide phase and downstream from the problem area during flood tide for several successive tidal cycles. The gilsonite moved from the points of injection to and throughout the problem area in suspension and in some degree along the bed; that is, most of the silt was deposited directly in the problem area, while a smaller amount was deposited elsewhere and moved into the problem area by transport along the model bed. After completion of a shoaling test on the model, the model was pooled, and the gilsonite that had been deposited in the channels was picked up and measured. No attempt was made to reproduce the actual volumes of prototype shoaling, inasmuch as the formation of deep deposits of gilsonite on the concrete bed of the model in areas exposed to the tidal currents would have been impossible. Instead the characteristics of the mixture and the method of introduction were varied through a cut-and-try process until the *distribution* of shoaling material throughout the problem area conformed to the measured distribution of shoaling in the prototype. Taken together, the reproduction of hydraulic elements, followed by reproduction of the distribution of shoaling, comprised the complete adjustment of the model.

The operating procedure developed during adjustment of the model —that is, the gilsonite-water mixture used, the volume introduced, the method of introduction, and the exact number of cycles elapsing after introduction of the material—was followed strictly during all tests of improvement plans. In order to assess correctly the effects of each proposed improvement plan on shoaling of the channels, a base test or test of existing prototype conditions was first recorded, and the measured amount of shoaling obtained during each test of an improvement plan was compared with that obtained during the base test.

The effectiveness of a given plan was then evaluated in terms of the percentile reduction or percentile increase in shoaling as compared with the base test.

Numerous plans were proposed and tested, and it was found that two plans, both designed to realign the currents to conform to the channel alignment, indicated reductions in shoaling of approximately 50 percent. Plan 1, which indicated a reduction of 47 percent, con-

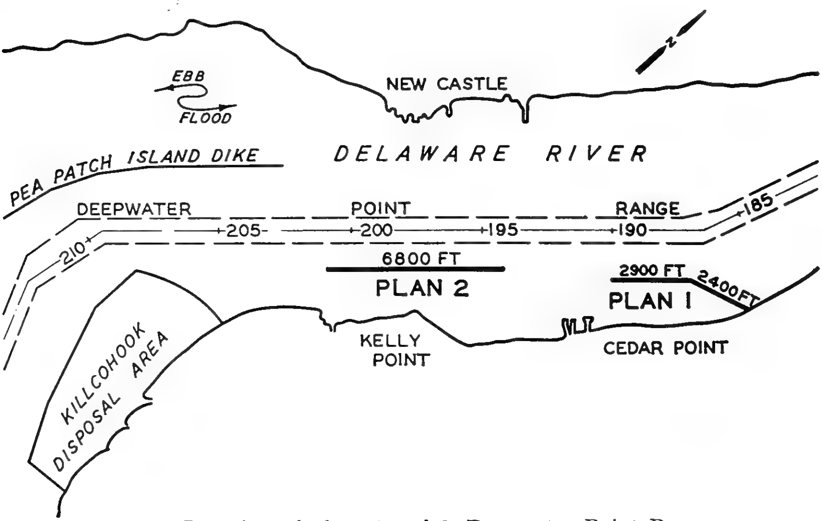

FIG. 5. Location of plans 1 and 2, Deepwater Point Range.

sisted of a dike beginning at a point 1,900 feet east of the center line of Deepwater Point Range, opposite channel station 189+500, extending upstream parallel to the channel for 2,900 feet, thence forming an angle of 151° and extending for 2,400 feet and tying in to the shore (Fig. 5). The top elevation of the dike was approximately 2 feet above mean high water. Plan 2, which indicated a reduction of 59 percent, consisted of a straight, 6,800-foot dike, beginning at a point 700 feet east of the channel center line opposite channel station 200+900 and extending upstream parallel to the channel to station 194+100 (Fig. 5). The top elevation of this dike was also about 2 feet above mean high water. It first appeared that plan 2, which effected a slightly greater reduction in shoaling than did plan 1, would be the better plan. On closer examination, however, it was found that current patterns over the problem area as influenced by plan 2 were not so satisfactory as for plan 1 (see Fig. 6). Furthermore, the plan 2 structure, being located in fairly deep water over its entire length, would be

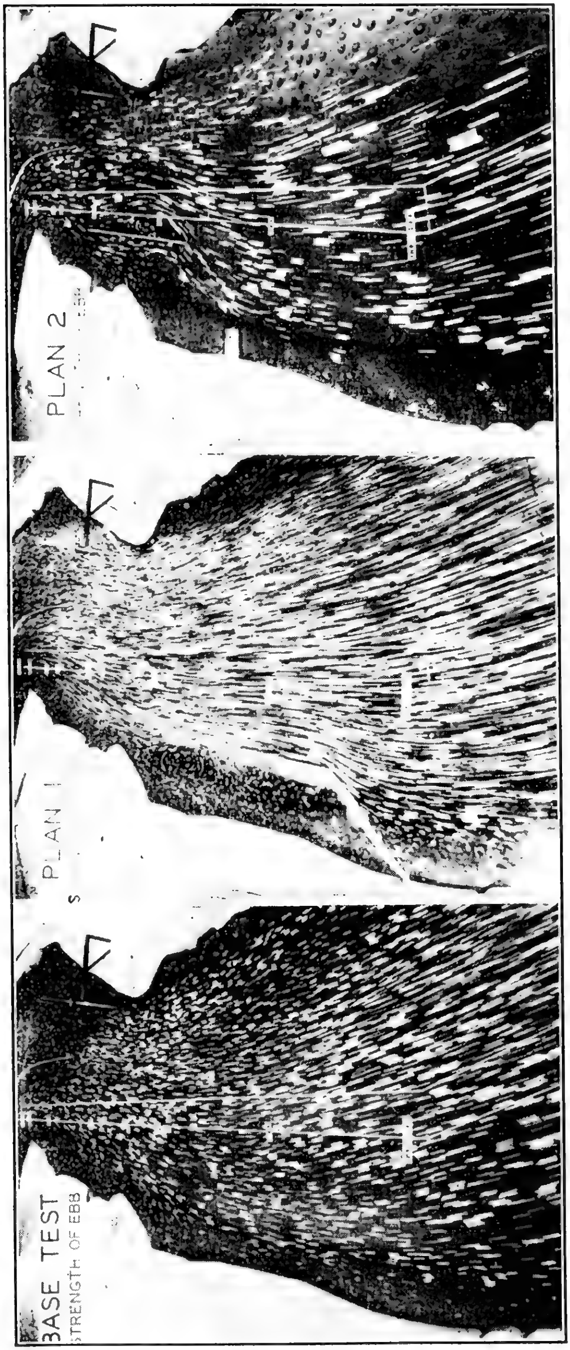

FIG. 6. Deepwater Point Range model studies; ebb-flow patterns.

considerably more expensive to construct in nature than would plan 1; therefore it was recommended that plan 1 be installed in the river.

Plan 1, now known as the Pennsville Dike, was constructed in the river during the period April, 1942, to June, 1943. A study of the effects of this dike on prototype shoaling during the period June, 1943, to November, 1946, has been made by the Philadelphia District Office of the Corps of Engineers. During this period, it was found that Deepwater Point Range shoaled at an average annual rate of 1,470,000 cubic yards, or a reduction in shoaling of 48 percent from the average rate before construction of the dike. The predicted decrease in shoaling for this structure, as obtained from the model study, was 47 percent. Construction of the dike effected some increase in the rate of shoaling in the lower end of Cherry Island Range, a short distance upstream from the Pennsville Dike; however, the increased shoaling in that locality was considerably less than one-half the reduction in Deepwater Point Range effected by the structure. Taking into account the initial cost of the structure, interest thereon, and the cost of maintenance, as against the cost of dredging material which would have deposited in Deepwater Point Range except for the dike, the actual monetary saving amounted to approximately $67,000 annually at the cost levels then prevailing. The study, conducted on an existing model of the Delaware River, cost somewhat less than $12,000 to perform.

SAVANNAH HARBOR, SAVANNAH RIVER

A problem somewhat related to the Deepwater Point Range problem, but nevertheless different in its basic features, is that of deposition of suspended silt in portions of tidal rivers and estuaries in which salinity and salinity currents play an important role in the process of sedimentation. As an example of an investigation of this type of problem by means of hydraulic models, the study of Savannah Harbor has been selected.

Savannah Harbor (see Fig. 7) comprises the lower 22 miles of the Savannah River and forms the navigable waterway from the port of Savannah, Georgia, to the Atlantic Ocean. At the time of the model study the channel was maintained to a depth of 30 feet below mean low water over a suitable width and was subject to shoaling in several reaches of the harbor. A large part of the silt carried by the Savannah River is in the form of colloidal or semi-colloidal suspension. An important property of these particles in suspension is that they exhibit no tendency to ball together and form deposits on the river bed, for the reason that the outer layer of each particle is charged with a negative electric potential. This potential being the same in all particles, the latter repel each other, and a state of complete dispersion prevails so long as the water is fresh. Contact with salt water, however, causes a base-exchange reaction, whereby the electric potential is instantly neutralized and a process of clotting, technically known as coagulation or flocculation, results. At first the lumps of coagulated material are quite small; however, as more and more particles are attached, the lumps attain sufficient size and

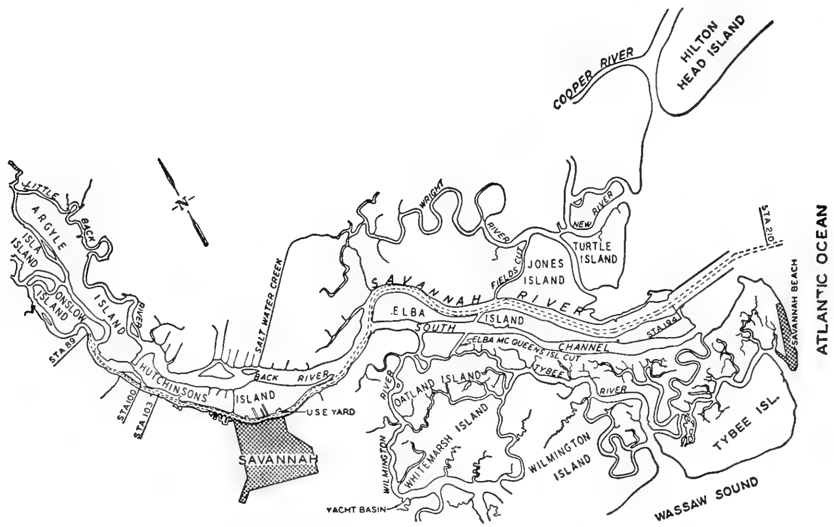

Fig. 7. Savannah Harbor model study.

weight to sink to the bottom, thus effecting deposits in the navigation channel.

The problem of channel shoaling due to flocculation of suspended silt by salt-water action is further complicated by the effects of salt water on the velocity of bottom currents. Owing to its greater density as compared with fresh water, salt water tends to occupy the lower layer of the channels as a wedge-shaped mass, with the point of the wedge upstream. The most pronounced effects of salt water on bottom currents, therefore, are to increase bottom flood velocities and decrease bottom ebb velocities, which effects reduce the normal preponderance of ebb flow over flood flow and thus decrease the net seaward movement of material being transported along the bottom.

The section of the harbor subject to heaviest shoaling is the lower 4-mile reach of Front River between the city of Savannah and the intersection of Front and Back rivers. In this reach, for normal conditions of tide and fresh-water discharge, the initial contact between salt water from the ocean and silt-laden fresh water from the upper watershed occurs. Furthermore, the effects of salt-water currents on bottom velocities in this reach of the harbor are very pronounced, there being a condition of almost complete stagnation on the bottom during the ebb period. The resultant of the above conditions is that very rapid shoaling occurs in the navigation channel, and extensive dredging, at an average annual cost of approximately $250,000, is required to maintain project depths in this relatively short length of channel.

The model used for a study of the above problem reproduced an area of the Atlantic Ocean from Wassaw Sound on the south to Hilton Head Island on the north and offshore to about the 40-foot contour of depth; the Savannah River from its mouth to the head of tide; and the maze of interconnecting tidal channels tributary to the Savannah River. The model was of the fixed-bed type, all channel and overbank areas being molded in concrete to scales of 1:1,000 horizontally and 1:150 vertically. Automatic tide controls reproduced the tides in the ocean portion of the model, and the scale discharge of fresh water, representing the fresh-water flow of the river, was introduced at the upstream end. The salinity of the model ocean was maintained at the measured salinity of the prototype, so that salinity currents and their effects were reproduced accurately throughout the model. No attempt was made to reproduce the prototype process of shoaling in the model; instead a comprehensive study was made of the effects of each plan on hydraulic conditions throughout the harbor, and on this basis the probable effects of the plan on prototype shoaling were predicted.

Plans designed and tested to reduce shoaling in lower Front River consisted in deepening, widening, and extending upstream the project channel, constructing submerged sills across the mouth of Back River, constructing a dam and tide gate in Back River and a dredge cut across Hutchinson Island above the city of Savannah, and replacing the tide gate of the latter-mentioned plan with a solid dam. Tests of widening, deepening, and otherwise improving the Front River project channel indicated that bottom ebb velocities in lower Front River could be increased appreciably by this method. As was expected, improvements in the hydraulic efficiency of the channel allowed the tide wave to run more freely and thus effected increases in velocities throughout Front River. Tests of submerged sills across the mouth of Back River indicated that this method would have little, if any, effect on velocities in Front River. By far the greatest increase in ebb velocity in Front River was effected by the tide gate in Back River and the Hutchinson Island cut. (Fig. 8).

Operation of this plan was such that the tide gate opened during the flood-tide period and the flood tide entered Back River normally; the gate closed at high-water slack; and, during the ebb-tide period,

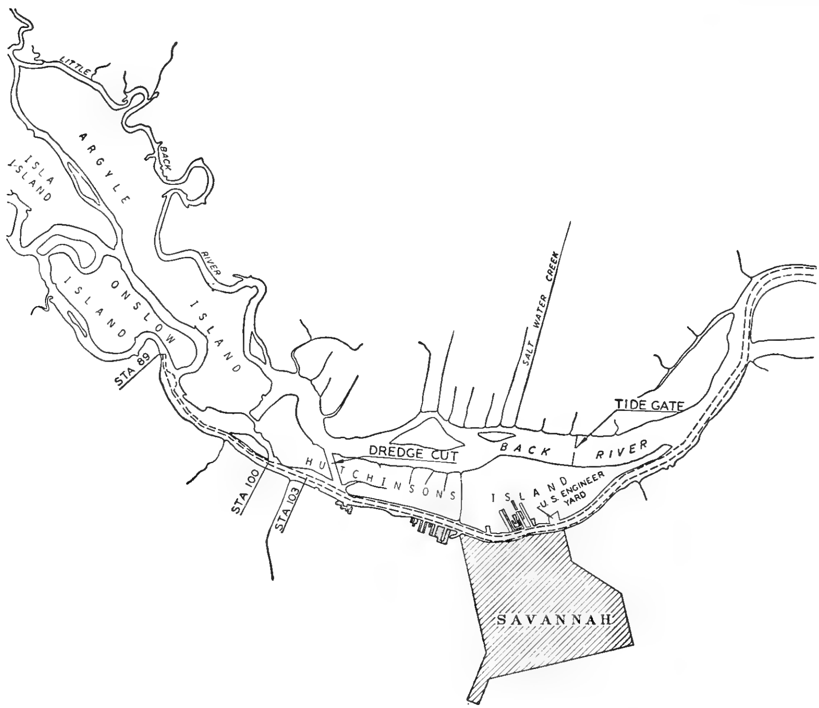

FIG. 8. Savannah Harbor model study; effect of tide gate in Back River.

the Back River tidal prism above the gate emptied through the Hutchinson Island cut and thence through lower Front River, thereby increasing ebb velocities in lower Front River to a large extent. Tests of replacing the tide gate with a solid dam indicated that this method would also effect large increases in velocity in lower Front River; however, with the solid dam instead of the tide gate, both flood and ebb velocities in Front River were increased. By varying the location of the tide gate or the solid dam in Back River, thus varying the portion of the Back River tidal prism that would be added to Front River by either of these plans, it was found that velocities in lower Front River could be increased up to a maximum of 4 to 5 feet per second. It was also found, however, from a study of the effects of the tide-gate and solid-dam plans on the harbor as a whole, that the method that added a sufficient portion of the Back River tidal prism to Front River to increase appreciably the velocities in lower Front River would also have the effect of decreasing the tidal prism of the harbor. A decrease in tidal prism might cause shoaling in areas of the harbor not subject to shoaling at present, because such decrease would be accompanied by decreases in mean current velocities of a magnitude proportional to the decrease in tidal prism. It was recommended, therefore, that it first be attempted to reduce shoaling in lower Front River by improving the hydraulic efficiency of the navigation channel and then, if additional works are required, to install either the tide-gate or the solid-dam plan, whichever effected only a slight reduction in the tidal prism of the harbor.

ABSECON INLET, NEW JERSEY

A fourth type of sedimentation problem, and one encountered frequently by the coastal districts of the Corps of Engineers, is that of shoaling of the entrance channel to a bay or estuary by the alongshore or littoral drift of sand, as influenced by the combined action of waves, tidal currents, and littoral currents. As an example of the investigation of this type of problem by means of hydraulic models, the study of Absecon Inlet, New Jersey, has been selected.

Absecon Inlet (see Fig. 9) is located on the coast of New Jersey and lies between Brigantine Beach on the north and Atlantic City Beach on the south. At the time of the model study a 400- by 20-foot channel was maintained through the inlet to afford access to the port of Atlantic City by coastal vessels and pleasure and fishing craft. The entrance channel was subject to very heavy shoaling and required frequent maintenance dredging; furthermore, because it was exposed to the direct attack of ocean waves, both navigation and dredging operations were extremely hazardous during winter months.

The predominant littoral drift at Absecon Inlet is from northeast to southwest, the sand being moved along Brigantine Beach, across the inlet, thence southwesterly along the Atlantic City Beach. This sand provides a continuous supply of material to the Atlantic City Beach and, since maintenance of the stability of this beach was of utmost importance, it was essential that a plan of improvement designed to reduce shoaling of the entrance channels should not reduce the supply of sand from beyond the inlet channel.

The model used for this study reproduced approximately 110 square miles of the Atlantic Ocean and Absecon Inlet to a point slightly above

Brigantine Bridge. The model was constructed of concrete with a movable-bed section molded in sand that extended from Ventnor, New Jersey, on the southwest to a point on Brigantine Beach approximately 22,000 feet northeast of the inlet, and offshore to about the 30-foot contour of depth in the ocean. The model was constructed to linear scale ratios of 1:500 horizontally and 1:100 vertically, and provisions

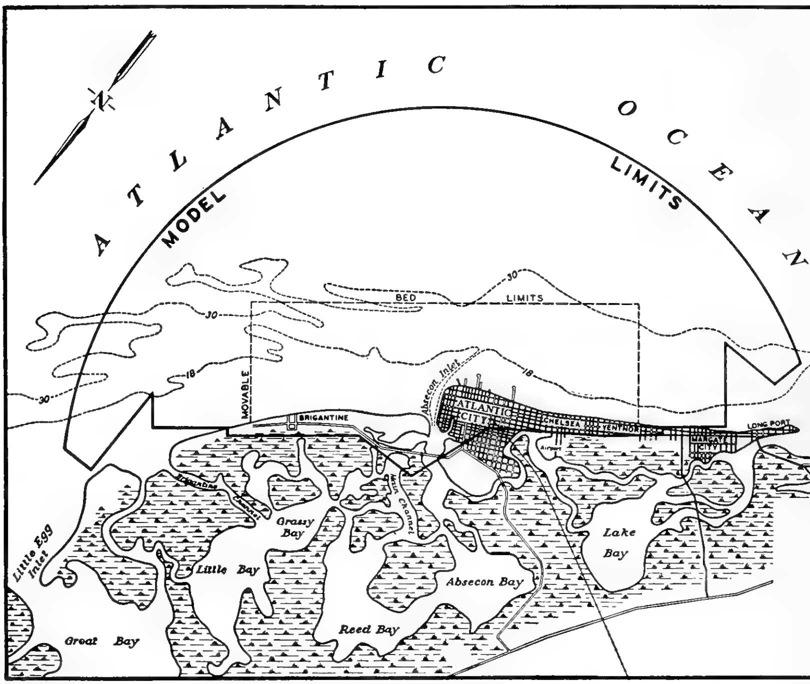

FIG. 9. Location map, Absecon Inlet model study.

were made for reproducing tides in the ocean and inlet, littoral currents parallel to shore in either direction, and waves from any direction from south to northeast.

As explained previously, the verification of a movable-bed model is of great importance, inasmuch as this process establishes the accuracy with which the model reproduces the bed-movement characteristics of the prototype and also establishes the time scale for bed movement. For the Absecon Inlet study, the verification period was selected as the period between prototype surveys of January, 1936, and January, 1939. The hydraulic forces in the model were then adjusted empirically until the movement of sand in the model was such that all changes in bed configurations which occurred during the 3-year period in the prototype were reproduced accurately. In addition, the model entrance channel was dredged periodically to depths shown on prototype after-dredging surveys, and it was found that the volume of maintenance dredging required in the model checked very closely with the volume dredged in the prototype during the 3-year verification period. This feature provided a further check on the accuracy of the model adjustment in that the volume of shoaling of the entrance channel, plus general changes in bed configurations, was reproduced.

Several types of jetty plans were tested to determine their effects on

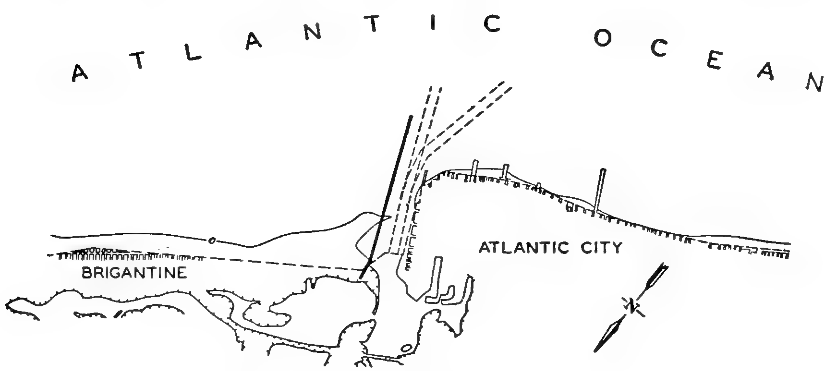

FIG. 10. Absecon Inlet model study.

channel shoaling and the stability of the Atlantic City Beach. The plan selected as the best (see Fig. 10) consisted of a north jetty 8,000 feet long and a south jetty 800 feet long. The first 1,000 feet of the north jetty was at elevation +8.0 feet MLW, the next 4,500 feet was at 0.0 MLW, and the remaining 2,500 feet was at +12.0 feet MLW. The low section of the jetty allowed sand to move across it and into the channel, from whence the sand was moved seaward by ebb currents in the inlet and thence back to the Atlantic City Beach by the action of waves. The south jetty sloped from elevation +9.0 feet MLW at the inner end to 0.0 MLW at the outer end. A large quantity of sand was trapped on the south side of this jetty, and the beaches were therefore improved in that area. During initial tests of this plan, it was noted that the navigation channel tended to shift to a new location parallel to and approximately 800 feet south of the north jetty; therefore subsequent tests involved relocating the channel in this position. The results of final tests of this plan indicated that maintenance dredging in the inlet would be reduced approximately 55 percent by its construction, and that the plan would have no detrimental effects on stability of the Atlantic City Beach. Furthermore, the high outer section of the north jetty would afford protection to boats navigating the channel and would make dredging operations in the seaward portion of the channel considerably less hazardous.

CONCLUSION

It has been demonstrated during this discussion that the adjustment and verification of the sedimentation model, and hence the accuracy of results to be obtained therefrom, are based on data obtained from comprehensive prototype investigations. The completeness and accuracy of such prototype studies are most essential, as the model study would produce erroneous results if its adjustment and verification were based on inaccurate or incomplete field data.

In the above connection, model-prototype confirmation studies are of inestimable value to the engineer who works with sedimentation models. After the installation of an improvement plan in the prototype as a result of a sedimentation model study, the question immediately arises as to how closely the functioning of this plan in nature corresponds to the model predictions. Where inconsistencies are revealed through such a confirmation study, model operating techniques may be improved to the end of eliminating such inconsistencies in the future. Model-prototype confirmation studies are believed to be of such importance to the further development of sedimentation model techniques, and thus to the solution of the problems involved, that plans for a confirmation study should be included as part of each comprehensive improvement plan that has involved study on a sedimentation model.

It is apparent that the sedimentation model has certain limitations, imposed primarily by the characteristics of the available model bed materials, the adequacy of prototype data, the distortions inherent in small-scale models used for such purposes, and the uncertainties that still exist regarding the mechanics of sediment movements in both model and prototype systems. These limitations are considered to be far outweighed, however, by the many advantages gained through the relatively inexpensive and positive expedient of model analysis as contrasted with the prohibitive and tremendous cost, effort, and hazard that would otherwise be involved in achieving similar solutions by trial and error in the field.

Although they do not embrace the entire field of model research, the four examples cited should be enough to demonstrate the broad capabilities of hydraulic models for the practical analysis of complex problems of sedimentation in natural and artificial channels. The rapid improvement of model techniques, together with the potentialities of generalized laboratory experiments of a fundamental nature, should correspondingly increase the scope of application.

It is to be understood that the hydraulic model is not proposed as a substitute for analytical design; nor can its use eliminate the need for extensive field investigations. The three are mutually supporting. The need for experimentation, however, is basically fostered by the fact that present-day knowledge of sedimentation phenomena and river hydraulics has not advanced to the point where such problems can be resolved by theory alone. Until that point is reached, the hydraulic model will continue to be a most useful expedient in providing information not obtainable by other means. Thus, in its usefulness to the engineer responsible for channel improvement, as in other problems of hydraulic engineering, the small-scale model occupies a place of great importance lying somewhere between the provinces of abstract theory and rule-of-thumb field engineering.

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*These references apply to the four examples described in the chapter.

Chapter 18

STREAM-CHANNEL CONTROL

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Stream-channel control is a term commonly applied to engineering projects intended to provide deeper water for navigation, hasten the runoff of flood waters or confine them within restricted limits, improve drainage of adjacent lands, or check stream bank erosion.

The principal channel-control methods are canalization of natural rivers by dams, with locks to pass boats or barges; open-channel regulation by training dikes, jetties, or wing dams to deflect channels into a more desirable alignment or confine them to lesser widths, with dikes or dams to close secondary or other undesirable channels and thus divert or concentrate the stream into a preferred course and, in some cases, ground sills, or weirs, to prevent undesired deepening of the bed by erosion; or dredging or other forms of excavation to enlarge existing channels, remove local bars or other obstructions, or form new channels which may be either larger, straighter, or different in alignment. Bank revetment by paving, riprap, or protective mattresses to retard erosion is commonly undertaken in connection with either of the methods of regulation, or often independently for protection of bordering lands. Earth levees and concrete or masonry flood walls are often built to confine flood waters in connection with channel-control projects. Impounding dams or reservoirs contribute to the channel control by restricting the size of flood flows and increasing low-water flows. Propagation of willows or other vegetation is often undertaken to aid in bank stabilization on small streams.

A large proportion of the major rivers are now extensively affected by channel-control works of one type or another. In the United States most of the larger river projects are carried on by the Corps of Engineers of the Department of the Army. Within the past 15 years there has also been very widespread construction of channel-control projects on small streams throughout the country, especially bank protection and check dams to retard erosion and runoff, constructed principally as part of the federal soil conservation and forestry programs. Straightening of channels by dredging or dragline excavation has been extensively undertaken to improve drainage and reduce flooding of valley farm lands in the central and southern United States. In Europe more effort has been devoted to improvement of smaller rivers for navigation, and to stabilization of steep mountain torrents, as described in treatises by Franzius (1936) and by Schoklitsch (1937), translated by Straub and Shulits, respectively. Young (1933) has summarized contrasts between European and American practices.

STREAM-CHANNEL PROCESSES

All natural streams carry sediment, derived from erosion of the soils and rocks in their drainage basins, and form sedimentary deposits, or alluvium, in places where the transporting capacity is locally decreased. Some alluvial deposits, such as channel bars, are temporary and may exist only for periods of minutes or days; others may become incorporated into flood plains and persist for centuries. Most streams therefore have their beds and banks formed mainly in their own sedimentary deposits, which they continually rework by eroding the banks in some places and redepositing the sediment farther downstream, unless artificially restrained.

The heavier materials, commonly gravel or coarse sand, are moved chiefly at flood stages and deposited chiefly in the deeper parts of the channel; finer sands usually accumulate chiefly as bars along the sides of the channel; and silts and clays are usually deposited chiefly in areas of shallow overflow on the flood-plain surface where velocities are least. Thus, as a stream channel shifts about in its valley, it sorts the alluvium into a sequence grading from finer material at the top to coarser sands or gravel below. Most channel-control works are concerned primarily with the trading processes by which sediment is ordinarily being removed by stream erosion at some places and redeposited elsewhere farther downstream.

It is natural for stream channels to be crooked, because channel patterns are governed mainly by resistance of the banks to erosion, and bank materials are normally variable in resistance. The formation of a sedimentary bar in a channel produces asymmetry in the path of flow and complementary asymmetry downstream, and induces formation of additional bars and sinuosities in the current. If the banks are sufficiently resistant, the channel as a whole may retain a straight or slightly curving path, but the bed will develop a series of bars alternating from side to side, with the main current following a sinuous pattern between them. Such sinuosity of flow within a relatively straight channel, called serpentining (Schoklitsch, 1937, pp. 148–149), may be observed in many straightened stream channels at low water.

Once lateral bank erosion starts, for any reason, and the channel is locally widened, the process is self-sustaining. The recession of the bank permits the current to wash more directly against the downstream side of the eroded area, and thus the erosion and bank recession are continued. Sediment accumulates on the opposite side of the channel, or inside of the bend—the result of lessening velocity at that place as the main current turns away—and the channel gradually shifts in the direction of bank attack. This is the process of meandering, which is responsible for most of the natural instability which channel-control works are intended to check or correct.

The term "meander" is usually applied to the relatively smooth, regular loops developed by a stream where the rate of deposition on the inside of the curve is approximately equal to the rate of erosion on the outer side, so that the channel does not change greatly in width but is shifted into a longer, curving course. This has been called "forced-cut meandering" (Melton, 1936). The process is basically the same when deposition fails to keep pace with the lateral erosion, or "advanced-cut meandering," but the effects are quite different, for the channel is widened and the opposite banks may become quite diverse in plan. Probably all natural streams tend to meander, but the type and extent of meander development vary widely. Figures 1 and 2 illustrate short sections of the Missouri River as it was in 1890, when advanced-cut meandering was prevalent, and in 1945, after artificial bank revetment and training dikes had restricted the rates of bank erosion and regularized the channel into a "forced-cut" meander pattern.

Stream meanders usually occur in series, for the development of one meander or bend tends to direct the current against the opposite bank below and thus initiate a second bend or meander, and so on down the stream. The continued growth of one meander bend also causes a progressive downstream shift in the point of incidence of the current against the opposite bank at the head of the next bend, and thus there is normally a downstream progression or sweep of bends, or meander loops. Figure 1 shows that Saline City Bend on the Missouri River migrated more than a mile downstream from 1890 to 1945, and Rushville Bend, shown in Fig. 2, migrated nearly two miles in the same period. Further migration of Rushville Bend obviously would destroy a section of railway, unless artificially restrained.

Meander loops develop to a fairly uniform maximum size on any one stream or part of a stream where conditions are similar. The con-

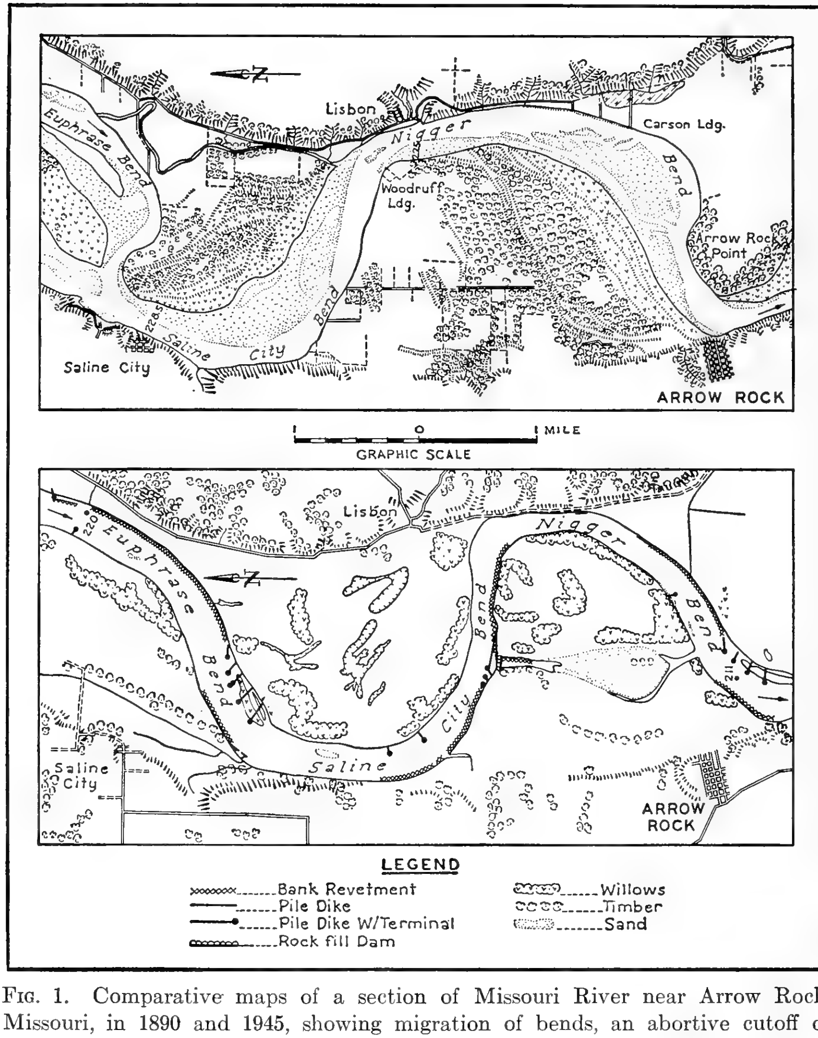

FIG. 1. Comparative maps of a section of Missouri River near Arrow Rock, Missouri, in 1890 and 1945, showing migration of bends, an abortive cutoff of 1915, and changes in land use and river pattern resulting from channel-stabilization works.

trolling factors limiting meander size are not fully known, but larger streams have larger meanders, and laboratory experiments with uniform rates of flow and homogeneous bank materials indicate that steeper axial slopes also produce larger meanders (Friedkin, 1945).

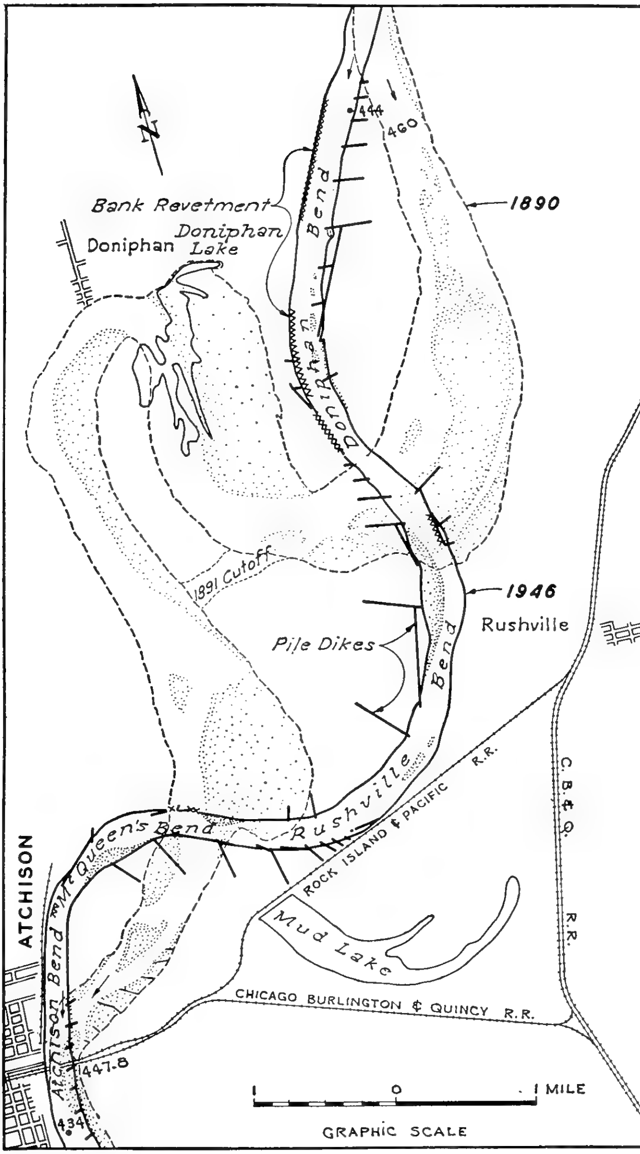

Fig. 2. Comparison of a section of Missouri River near Atchison, Kansas, as it was mapped in 1890 and in 1945, showing narrowing and regularization of the channel by training dikes and bank revetment. Downstream migration of Rushville Bend, and location of an 1891 cutoff which isolated the former river port of Doniphan, are also shown. The 1946 bank line was mapped late in 1945.

The growth of meanders is often stopped by development of shorter chute channels across the bars formed on the inside of the bends. Chutes may develop because the resistance to flow around the lengthening bend becomes greater than across the bar, or because changes in alignment caused by channel shifting upstream tend to direct flow across the bar inside the bend.

In natural streams many bends and meander loops are abandoned because of cutoffs resulting from adjacent bends migrating gradually into each other, or from channel avulsions across the necks between adjacent or even more distant bends during periods of overbank flooding. Most natural cutoffs of the first type are apparently due to relatively resistant deposits in the alluvium, which check the migration of one bend until it is overtaken by the downstream movement of another (Hearn, 1932; Matthes, 1941; Fisk, 1944). During a cutoff of this type on the Missouri River in 1880, a deep bed of clay held a neck only 8 feet wide for 24 hours between adjoining bends 4½ miles apart by river distance (Church, 1881, p. 1623). The 1891 cutoff shown in Fig. 2 was a Missouri River avulsion of the second type, across a narrow meander neck, by erosion of overbank flood water (Fox, 1892, p. 3289). A partial avulsion of the same type occurred on the Missouri River at Saline City Bend in 1915, as shown in Fig. 1, but the river diversion was not complete and the chute channel was subsequently shut off by bank-protection works and a rock-fill dam (McIndoe, 1916, p. 2649). The cutoff of several bends or meanders by a single avulsion seems characteristic of aggrading rivers, such as the Middle Rio Grande above Elephant Butte Reservoir (Happ, 1948, p. 1197 and Fig. 2, Plate I). Meander cutoffs or shortening by chute developments reduce channel lengths and increase slopes and hence are generally beneficial for reducing flood heights or improving drainage; but they may cause much local damage by channel shifting and bank erosion, and resulting unstable bed conditions that may interfere with navigation.

Natural streams flowing on alluvial beds normally develop alternating series of deep and relatively narrow pools, typically formed along the concave sides of bends, and shallow, wider reaches between bends where the main current crosses the channel diagonally from the lower end of one pool to the upper end of the next. During high flows the pools or bends tend to scour deeper, while the crossing bars are built higher by sediment deposition, although deposition does not equal rise in stage and hence water depth increases on the bars. When the stage falls, there is erosion from the top of the crossing bars and some filling in the pools; but, as low-stage activity is less effective, the general shape of the bed usually reflects mainly the flood-stage influence. At low water the stream consists of alternating deep pools of slight slope, and steeper slopes over the crossing bars where the depths become critical for navigation purposes, and dredging is often necessary unless the water depth can be increased by confining the width of low-water flow. Dikes or other channel-training or -contraction works lose their value if the channel shifts, and hence maintenance of effective channel improvements for navigation requires that banks be stabilized sufficiently to maintain the general channel alignment. Experience indicates that a channel of gradual curvature, with the size and radius of bends determined for each stream by experiment but often shaped to smaller radius toward their lower ends, and the concave banks protected by revetment, generally will maintain itself most satisfactorily. Channel regulation for navigation purposes is usually directed toward this objective.

IMPROVEMENTS OF RIVERS FOR FLOOD CONTROL AND NAVIGATION

Lower Mississippi River

Flood protection is the most important problem in the Lower Mississippi Valley, below the mouth of the Ohio River. Low levees were built by the early colonial settlers and gradually extended and raised by local interests. After establishment of the Mississippi River Commission, in 1879, river regulation was attempted by contraction with permeable dikes and closure of secondary channels, supplemented by dredging where necessary for navigation, and construction of levees that were expected to aid navigation by confining flood waters and thus inducing scour of the channel. The dikes and closure dams were generally inadequate, however, and dredging came to be the accepted method of improvement for navigation. The levees were also inadequate to withstand major floods and were topped or broken from time to time.

A more comprehensive federal flood-control project was adopted after the great flood of 1927. The levees have been greatly improved, so that they have withstood all floods since 1927; auxiliary leveed floodways have been provided to carry part of major floods past the city of Cairo and along the Atchafalaya River, which follows an old abandoned course of the Mississippi from the mouth of Red River to the Gulf at a point about 150 miles west of the present Mississippi mouth; the Bonnet Carre spillway has been constructed to divert part of major floods eastward to the Gulf through Lake Pontchartrain in order to give added protection to the city of New Orleans; the river has been shortened about 170 miles by cutoffs and opening chutes; several reservoirs have been constructed for alleviation of floods in parts of the Alluvial Valley affected by the tributary St. Francis and Yazoo rivers. An additional west-side auxiliary floodway was planned between the Arkansas and Red rivers, but there was considerable opposition to this feature and it was later eliminated from the plan.

Most of the 30,000 square miles of alluvial lands are now protected by about 2,679 miles of levees which reach heights of 30 feet in places and have a volume aggregating about 1,238 million cubic yards. The levees confine flood waters and hence increase stage heights; according to a tabulation given by Matthes (1948) the increase in stage heights was 6 to 15 feet at various points of measurement, before channel shortening by cutoffs.

Permeable pile dikes,* of heavier construction than those which proved inadequate during earlier years, are the principal means of training and contracting the channel, restricting the low-water channel to about its normal average width and thus eliminating local sections of excessive width where shoaling on the crossing bars was most troublesome. The pile dikes are set considerably below the top of the river banks, but sedimentation around them, followed by growth of vegetation on the sedimentary deposits, is usually expected to build up the diked area to full bank height. Sand-fill dams and dikes, built by hydraulic dredging, are used in many places to direct the current or close off secondary channels; these sand dams are not expected to be permanent but serve a temporary purpose (Ferguson, 1940, p. 9). The concave banks on the outside of bends are revetted to prevent excessive caving, chiefly by concrete mattresses of various types sunk below low water from barges, and by concrete or asphalt paving above low water. Underwater paving with a sand-asphalt mixture has been tried experimentally (Senour, 1948). In 1948 it was reported that 163 miles of operative bank revetments were in place.

Early channel cutoffs for navigation improvement were not successful (Elliott, 1932, p. 280; Ferguson, 1940, p. 15), but a natural cutoff in 1929 and 15 artificial cutoffs between 1932 and 1943, together with dredging and enlargement of chutes, shortened the low-water channel about 170 miles, or about 25 percent, between Memphis and Baton Rouge, with very satisfactory results. The channel shortening is

* In American engineering practice, the term "dike" is usually applied to rows of wooden piles fastened together by timbers or cables.

credited with lowering overbank flood stages by as much as 13 to 14 feet at Arkansas City, 9 to 10 feet at Vicksburg, and lesser amounts elsewhere, and thereby increasing channel capacities by 100,000 to 700,000 or 800,000 cubic feet per second (Annual Report of the Chief of Engineers, 1943). Other benefits included elimination of need for an auxiliary floodway between the Arkansas and Red rivers or equivalent increase in levee heights, and increased low-water depths which made feasible an increase from 9 to 12 feet in the navigation project depth in 1944 (Matthes, 1948).

It has been estimated that caving banks add about 800,000,000 cubic yards of sediment to the lower Mississippi annually, and that most of this material comes to rest on bars immediately downstream (Senour, 1948). This is believed to be the principal source of the sand that must be dredged each year in order to maintain the navigation channel. Maintenance of the navigation channel 9 feet deep and 300 feet wide required dredging about 43 million cubic yards from 64 locations during the year ending June 30, 1948, in comparison with an average of 30 million cubic yards annually since 1928, although as much as 75 million cubic yards has been required in years of extreme low water of long duration (U. S. Dept. of Army, 1948, p. 3013). It is reported that hydrographic surveys show no general tendency toward aggradation of the river bed within the period of records (Senour, 1947).

Dredging for navigation improvement was first undertaken in Southwest Pass, one of the river mouths, in 1839, and has been continued intermittently but with generally increasing volume. Jetties to narrow and deepen the mouth of South Pass were begun in 1875, and similar jetties were later built at the mouth of Southwest Pass. These jetties, with repairs and extensions, are still maintained, and they have been outstandingly successful. Below the mouth of Red River the Mississippi maintains a relatively deep and narrow channel in thick clay deposits, and the banks have been generally quite stable during the period of records. A navigation channel 35 feet deep is maintained up to Baton Rouge, 233 miles above the Head of Passes, and levees have been built close to the banks without excessive caving. The difference between this section and the variable channel widths and rapid bank caving farther upstream is ascribed to the greater resistance of the clay banks to erosion, in contrast to the more sandy banks upstream (Fisk, 1944, p. 53).

Middle Mississippi River

In the middle section of the Mississippi River, between the Missouri and the Ohio rivers, levees provide flood protection for agricultural lands of the alluvial plain, and a navigation channel 9 feet deep is maintained by regulating works for closing sloughs and secondary channels and narrowing the river, by building new banks where natural width is excessive, by protecting the banks from erosion by revetment, by dredging as required for temporary channel maintenance, and by construction of a lock and canal around the Chain of Rocks, a series of rock ledges in the channel just above St. Louis where swift currents and shallow depths have been a menace to navigation at low stages. Conditions at Chain of Rocks are reported to have been aggravated by effects of dredging and scouring of contracted channel sections below, which are credited with lowering the low-water plane at St. Louis about 8 feet since 1881 (U. S. Congress, 1940, p. 26). The entire navigation project, including Chain of Rocks improvements, was about 51 percent complete in 1948. Maintenance operations during the year ending June 30, 1948, included dredging about 4.7 million cubic yards from 41 shoals and repair of dikes and bank revetments (Annual Report of the Chief of Engineers, 1948, pp. 1505–1507).

UPPER MISSISSIPPI RIVER

The upper Mississippi River, above the mouth of the Missouri, is a comparatively stable stream, with low banks that are not generally subject to excessive erosion. It has a much smaller range of flood and low-water stages than the Ohio, Missouri, or lower Mississippi, and flood damage is not a major problem, although alluvial lands below Rock Island are protected by levees. The gradient is low, averaging about 0.35 feet per mile except in short stretches of rock-floored rapids in the vicinity of Rock Island and Keokuk. Early work was concerned chiefly with improvements for navigation at the Rock Island and Keokuk rapids, first by rock removal and later by lateral locks, and generally unsuccessful efforts to maintain channels of 4½ feet, and later 6 feet, by dredging, regulation, and contraction works. Two low locks and dams were built in the vicinity of St. Paul in 1894 and 1905, and a power dam, with supplementary navigation locks, which was constructed at the Keokuk rapids by private interests in 1913, greatly improved navigation conditions in that locality.

In 1930 a project was adopted for a navigation channel 9 feet deep, by canalization with supplementary dredging and contraction works, and continued operation of several headwater reservoirs constructed under earlier projects for improvement of low-water flows. Slack-water navigation from near the mouth of the Missouri to Minneapolis, a distance of about 658 miles, is now provided by 26 locks and dams, including the Keokuk power dam. All navigation dams are of overflow type, with unusually large gates to pass heavy ice flows, and sills approximately at river bed in order not to interfere seriously with flood discharge.

In 1940 no serious trouble was anticipated from sedimentation in the pools formed by the navigation dams, as no unusual difficulty had been encountered in maintenance of the navigation channels at the head of Lake Pepin and in the pool formed by Keokuk power dam, although the latter, which had an original length of 60 miles, has been reported to have lost about 23 percent of capacity in 15 years, most of the sediment being soft mud deposited in the shallower areas and along sides of the main channel without seriously interfering with the navigation channel (U. S. Congress, 1940, pp. 66–67). There has been considerable deposition on the flood plain and in the lower parts of some tributary valleys, however, and it is apparent that maintenance dredging will have to be continued in the pools (Hathaway, 1948). Large quantities of sand are brought in by the tributary Chippewa and Wisconsin rivers, and the delta or fan of the Chippewa long ago blocked the Mississippi and formed Lake Pepin, a ponded section of the main river about 21 miles long with maximum water depth of about 50 feet. Continued sand inflow requires dredging 250,000 to 300,000 yards annually to maintain the navigation channel immediately below the mounth of the Chippewa (U. S. Congress, 1940, p. 66).

The navigation project as a whole, including proposed extension above St. Anthony's Falls at Minneapolis, was about 75 percent complete in 1948. During the year ending June 30, 1948, maintenance dredging necessary at 116 localities amounted to a total of more than 5 million cubic yards.

OHIO RIVER

The Ohio River was a major route of travel and commerce in the days of shallow-draft steamboats, and it is today an outstanding example of a major river canalized for barge transportation. Its present commercial importance is due to the heavy and bulky freight traffic required by the coal, iron, and steel industries concentrated in the upper Ohio Basin. A canal around the Louisville rapids was opened in 1830, and construction of locks and dams to improve navigation in the Pittsburgh area was initiated in 1879, but it is reported that automobiles were driven across the river bed, at places 45 to 75 miles below Pittsburgh, during low water in 1908 before canalization was complete (Duis, 1944). A series of 46 locks and dams now provides a channel of 9 feet depth, at low stage, in a series of slack-water pools for a distance of 962 miles from Pittsburgh to within 19 miles of the confluence with the Mississippi River. The dams are of the overflow type, entirely submerged at high water, and all but one are fitted with movable wickets or gates that can be raised or closed to maintain pool levels during periods of low flow, and lowered or opened to pass high flows with relatively little obstruction to the current. There are 42 low-lift locks with dams on which wickets can be lowered to permit uninterrupted navigation at medium river stages; three locks of moderate lift with dams that cannot be navigated, and one dam, at the rock-floored "Falls of the Ohio" near Louisville, which can be navigated only at very high river stages, so that boats usually pass through a canal about 2 miles long (U. S. War Department, 1939, pp. 134–137).

The existing dams control water levels at low stages, but they are not close enough to provide continuous channels 9 feet deep and 500 to 750 feet wide, as required for the barge traffic, without dredging and contraction works. It is therefore expected that such supplemental works will continue to be necessary. Contraction works consist mostly of low dams to close secondary channels behind islands and thus concentrate the current, spur dikes to straighten wide, shallow reaches, and bank revetments.

The stream banks are generally stable, and bank erosion is not a serious problem except in places along the lower Ohio where it is locally severe. Most of the channel dredging and considerable bank revetment are required in this section. Maintenance dredging during the fiscal year 1948 amounted to 5.6 million cubic yards on the entire Ohio River, about 94 percent of which was in the lower 58 percent of the river length (U. S. Dept. of Army, 1948, p. 1810). Most of the dredging is believed to result from local sediment accumulations a short distance downstream from areas of active bank erosion, it being reported in 1935 that the pools showed no progressive silting, according to comparisons of surveys made in 1911–1914 prior to construction of most of the dams, and again in 1929 after the river had been completely canalized and about half the dams had been in operation 10 years or more (U. S. Congress, 1936, pp. 179–180).

The lower parts of the Monongahela, Allegheny, and Kanawha rivers are integral parts of the important Ohio waterway system, and they are canalized by locks and dams similar to those on the Ohio. Lower parts of the tributary Muskingum, Little Kanawha, Big Sandy, Kentucky, Green and Cumberland river systems are also canalized by low locks and dams, but these streams have less traffic, and shallower channels are provided, and in some instances the locks are no longer operational. Only the Big Sandy and Cumberland projects are considered worthy of modernization.

The Tennessee River, largest tributary of the Ohio, is canalized by high dams built by the Tennessee Valley Authority principally for electric power production. This might be considered an extreme form of channel control, in which the river is converted into a continuous series of reservoirs.

The entire Ohio River system of 137 locks and dams provides nearly 3,000 miles of canalized channels.

MISSOURI RIVER

The Missouri River was an important traffic route during the period of western settlement, but shallow-draft steamboat navigation practically ceased by 1880. The Missouri River Commission, established in 1884, inaugurated a policy of regulation by training dikes, bank revetment, and dredging, which was carried on by the Commission in a small way until 1902, and subsequently by the Corps of Engineers, but effective results were not obtained until after 1928, when the scale of work was increased. The regulation works for a channel 6 feet deep were sufficiently complete so that regular barge transport was inaugurated up to Kansas City in 1935, and extended in 1939 to Omaha, 632 miles above the mouth. In 1945 the project was modified to provide a navigation channel 9 feet deep and 300 feet wide to Sioux City, 760 miles above the mouth. This project is about 85 percent complete. The Fort Peck multiple-purpose reservoir on the headwaters provides supplemental water at times of deficient natural discharge.

In its natural state the Missouri River below Sioux City had many sand bars and islands within a channel varying from 1,500 feet to 1 mile in width, meandering irregularly within a flood plain $1\frac{1}{2}$ to more than 10 miles wide, underlain by about 100 feet of alluvial deposits which are mostly sand, with a surficial silt and clay cover generally less than 10 feet thick. Bank erosion was very active, and shifting channels were a serious hazard both to navigation and to use of the alluvial plain for agriculture.

Now most of the river below Sioux City has been converted into a narrower, regularly curving channel with comparatively stable banks, as illustrated in Figs. 1 and 2. The low-water channel widths are generally 700 to 1,100 feet, increasing progressively downstream, with bends 2 to 5 miles long having a minimum radius of 4,000 feet and maximum radius of about 20,000 feet, the optimum radius being 7,000 to 10,000 feet, increasing downstream. Where possible, the radius of curvature is made to decrease from head to foot through a bend.

Regulation has been accomplished chiefly by permeable pile training dikes, revetment to protect concave banks along the desired alignment, rock-filled dams to close chutes, and dredging and dragline excavation to hasten the adjustments and cut off a number of particularly sharp or long bends. The first cutoff was made especially to equalize abnormal disparities in slope immediately above and below the mouth of the Platte River in Nebraska, which has a much steeper slope and delivers more bed-load sand to the Missouri than the latter can readily carry away (Neff, 1940).

The permeable dikes, consisting of rows of clumps of piles fastened together and extending out from the bank, or parallel to the bank, are especially effective because of the large sediment load of the Missouri. The dikes retard velocity sufficiently to cause deposition behind them, which in turn helps to stabilize the dikes and induce further deposition. In a few months sand fills 10 to 20 feet deep may accumulate, over which flows are retarded sufficiently to deposit silt in which a thick growth of willows soon appears and further stabilizes the deposit. This effects a prograding of the high banks, adding to the area of overbank flood plain and helping turn the channel toward the opposite side. In some places where the channel impinges against the bluffs, shallow bedrock prevents driving piles, and loose rock dikes are used. The most critical factor is protection of the concave banks against lateral erosion. Bank revetment usually consists of woven willow or lumber mattresses, weighted with stone to sink them into place below the water line, and anchored by piles driven along their landward sides. Above the low-water line the banks are paved with stone (Walsh, 1936).

Dredging is necessary to maintain required depth for navigation across many bars during periods of low water, although maintenance dredging is expected to decrease as the channel is more completely stabilized. During the fiscal year 1948 such dredging amounted to 8.5 million cubic yards at 48 localities (U. S. Dept. of Army, 1948).

The regulation works for navigation reduce low-water channel cross sections but this is expected to be offset by increased hydraulic efficiency at high stages so that discharge capacity will be at least maintained, and probably increased. Studies reported by Whipple (1942), following theoretical analyses by Straub (1935), indicated that the improved channel may be expected to scour itself deeper because of increased sediment-carrying capacity.

The protection of the alluvial lands from bank erosion and channel avulsions is a very important result of the channel stabilization, and construction of a comprehensive system of levees to protect these alluvial lands from flooding has been started, which would not have been practicable before the channel stabilization. It is not yet apparent how confinement of overbank floods by the levees will influence channel control (Hathaway, 1948).

OTHER RIVERS

There are many other important channel-control projects, but the Mississippi, Ohio, and Missouri river projects illustrate most of the problems and methods on large American rivers. A great deal of dredging and other work is done to improve and maintain navigation channels in the lower courses of Atlantic and Gulf Coast rivers (Boggs, 1929; Hathaway, 1948; U. S. Dept. of Army, 1948). An important canalized waterway is maintained on parts of the Tombigbee and Warrior rivers in Alabama (U. S. Dept. of Army, 1948, pp. 977–984). The canalized Illinois River and connecting canal to Lake Michigan provide an important navigable route from the Great Lakes to the Mississippi system (Smith, 1933; U. S. Dept. of Army, 1948, pp. 2281–2294). Channel-control works are important on several sections of the Rio Grande; they are partly involved in stabilization of the international boundary with Mexico (Lawson, 1937) and partly involved in serious local flood-control problems aggravated by heavy sediment loads and river aggradation (Fiock, 1934; Stevens, 1938; Happ, 1948; U. S. Dept. of Army, 1948, pp. 1341–1342). Improvement of the Columbia River and tributaries for navigation, in connection with large power and flood-control dams and irrigation developments, is now in a very active stage (Tudor, 1945; U. S. Dept. of Army, 1948, pp. 2676–2720). Channel improvement on the Sacramento River in California involves both navigation and flood-control interests and is interrelated with irrigation developments and the extreme sedimentation problem resulting from early hydraulic mining in the Sierra Nevada gold fields (Gilbert, 1917; Grunsky, 1929; Robertson, 1942; U. S. Dept. of Army, 1948, pp. 2620–2625, 2657–2659, 2979–2996). In the Los Angeles area severe local flood problems are concerned with maintenance and improvement of stream channels across alluvial fans where aggradation is the natural condition (Mathias, 1941; U. S. Dept. of Army, 1948, pp. 2523–2545). Stream-bed retrogression as a result of sediment detention in Lake Mead is a major factor in channel control on the lower Colorado River (Stevens, 1938; Stanley, 1948).

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Chapter 19

DEBRIS CONTROL

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THE PROBLEM

The control of debris is a specialized consideration in the field of sedimentation. In this sense, the term debris has come to mean sediment particles usually ranging in size from fine sand to the largest of boulders (see Fig. 1). The term is also associated with the movement or deposit of such material in considerable quantity. Extensive debris deposits, called debris cones and alluvial fans, are well-known and easily recognizable geological features found at the mouths of steep canyon drainage areas. The conditions and processes that lead to formation of debris cones are beyond the scope of this discussion but may be found in most standard textbooks on geology.

Debris becomes a problem and requires control when man's development and use of land encroach on the area where flood flows carry and deposit debris. Many existing problems of this nature would have been avoided if original settlers had recognized such areas and been aware of the attendant erosion processes.

Debris-producing areas exist in many places throughout the world. The three areas mentioned below, all in the western United States, are those for which detailed information is readily available and in which different methods of control have been practiced.

In southern California, debris-cone areas are common along the west face of the coastal ranges. Of particular concern is the area along the base of the San Gabriel Mountains, within Los Angeles County. These mountains rise about 3,000 feet and more in a space of 1 to 3 miles. They are rugged in character, drained by precipitous canyons, and have a surface of shattered, deeply weathered rock covered by a thin mantle of coarse, rocky soils. Intensive urban and suburban development has encroached upon, and in some places completely occupied, the debris-cone areas at the mouths of the canyons. In those areas debris flows may be large and may cause great damage (Dodge, 1947).

In Utah a somewhat similar situation exists along the west front of the Wasatch Mountains. In this area debris flows contain a greater

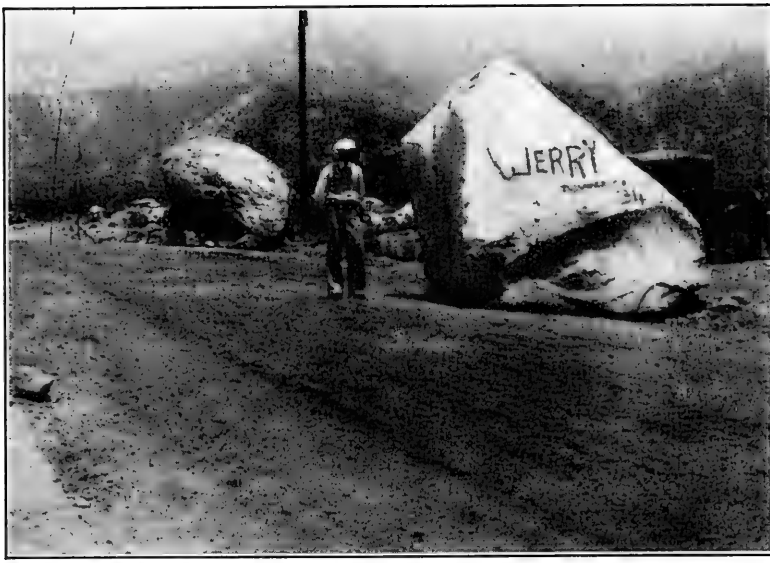

Fig. 1. La Crescenta area, San Gabriel Mountains. The flood that moved these boulders onto the pavement came from Dunsmuir Canyon, with a drainage area of about 500 acres. The boulder in the foreground was measured and weight calculated to be 40 tons.

percentage of fine alluvium and have been described as mud and rock flows. The development in the debris areas, being mostly rural in character, is less intensive than that in Los Angeles County, and damage caused by debris flows is proportionately smaller (Woolley, 1946; Alter, 1930).

In northern California, on tributaries of the Sacramento River, the debris problem is entirely man-made. Hydraulic mining operations, which began at the time of the gold rush, resulted in the washing of huge quantities of debris down to the principal streams. This material, which was carried out to the valley floor by subsequent floods, filled the river channels and caused flood overflow of adjacent lands (Parsons, 1947).

FACTORS THAT INFLUENCE THE PROBLEM

The successful solution of debris-control problems depends on accurate appraisal of physical conditions in the problem area and the development of an adequate method of control that is both suited to those physical conditions and within the economically justified cost.

DEBRIS QUANTITIES

Control of debris by trapping or storing material carried in channels involves estimation of the amount of debris that may be expected either to result from a single large flood or to accumulate over a period of years. No practical method exists for gaging debris while in transit. The only source of data therefore is from comparison surveys of areas where debris is deposited. Such records are extremely meager. In Los Angeles County, in the area at the base of the San Gabriel Mountains, the average debris production resulting from a major flood in 1934, as estimated from deposits over the area, was 88,000 cubic yards per square mile of drainage area. This flood occurred a few months after most of the mountain drainage area involved had been denuded by fire. Four years later, in 1938, another major flood in the same area produced debris, as measured in 8 debris basins constructed in the interim, at an average rate of about 75,000 cubic yards per square mile of drainage area, with a maximum rate of 124,000 cubic yards per square mile. Mean annual rates at the same basins, as tentatively indicated from only about 10 years of record, average 16,000 cubic yards per square mile of drainage area, with a maximum of 22,300 cubic yards per square mile. These rates, from a combined drainage area of about 6.5 square miles, are the highest known to the writer. Debris-production rates from nearby but larger drainage areas are substantially smaller (Dodge, 1947). Such data are useful in planning debris-control programs for similar areas (Douma, 1947).

However, no method exists for applying this information directly to the estimation of debris-production potentialities of areas where the physical conditions are appreciably different. In such cases, the only alternative is to consider the physical conditions that lead to debris production in the problem area and, by comparison with conditions in an area for which records exist, arrive at an approximate estimate.

DRAINAGE-AREA CONDITIONS

The principal physical conditions that, in combination, usually characterize debris-producing areas are:

Topography. Debris-producing areas are usually rugged and precipitous, covered only with sparse vegetation. Main drainage courses are narrow, steep, and conducive to the turbulent high-velocity runoff necessary for transportation of large quantities of debris.

Geology. Geologic features conducive to debris production are slide areas, shattered and deeply weathered rock, and coarse, porous, rocky soils.

Hydrology. Debris-producing areas are usually those having low annual rainfall, classed as semi-arid. In such areas, long periods of little rainfall result in only sparse vegetation and permit the weathering and accumulation of debris in quantity on the watershed and in the drainage channels. Such areas are subject to occasional short-duration high-intensity rainfall that produces flash floods having high peak discharges capable of collecting and transporting large quantities of debris.

Fire. In areas having the characteristics described above, the only retarding influence on excessive erosion is the vegetal cover. When the plant growth, even though sparse, is destroyed, the rate of debris production resulting from a given rainfall is enormously increased, and it diminishes only gradually as new growth becomes established. In appraising the debris-production potentialities of any area, therefore, the possibility of complete denudation by fire should always be considered.

Economic Considerations

Economic factors are as varied as the developments to be protected. Obviously, the cost of control works should not exceed the value of benefits to be derived, except where intangible benefits such as protection of life are an important part of the problem. In highly developed urban and suburban areas, potential damage is tremendous, and control measures must be positive. Consider, for example, the flood on January 1, 1934, in the La Crescenta area. This flood, from a number of individual canyons having a total drainage area of about 7.5 square miles, lasted less than 15 minutes, deposited about 660,000 cubic yards of debris over the area, killed 42 people, and destroyed 500 homes. The total damage was estimated at $5,000,000. Although such floods are infrequent (a factor that encourages development of such areas), costly control works are well justified.

In Utah, where the development to be protected is generally rural, most of the damage results from debris deposition on farm land. The benefits from debris control are consequently not so great as in urban areas, and control measures are required that are less costly and perhaps less positive.

In the Sacramento River areas, the production of debris can be controlled by limitation of hydraulic mining operations. Conversely, debris-control structures are installed primarily to permit continuation of mining operations and are justified by the return from those operations.

One other economic factor sometimes missed is that debris cones are natural water-percolating areas and are frequently important in maintaining underground water supplies. In semi-arid areas, reduction of water supply by debris-control works may be more serious than the damage from debris.

METHODS OF CONTROL

The methods of debris control most generally used are briefly described below. The applicability and effectiveness of any of these methods depend on the physical characteristics of the area involved.

Watershed Treatment

The most direct approach to the problem is concerned with stabilization of the drainage area for the purpose of reducing erosion to a minimum. Such methods consist in establishing or encouraging plant growth, terracing, and preventing fires. These methods can be used singly or in combination.

Artificial establishment or increase in plant growth depends mainly on rainfall supply, soil type, and soil fertility; the availability of plant types that can thrive under the given conditions; and, lastly, adequate protection of the cover growth from fire.

Terracing to form long, narrow, on-contour storage basins, serves to trap runoff on the watershed and prevent its concentration into debris-carrying flow. The trapped runoff is dissipated by percolation into the ground and by evaporation. By increasing the runoff retained on the watershed, terracing may also result in improvement of cover growth. Terracing is not applicable in areas that are rugged and rocky and have only a thin soil mantle. Terrace basins can be dangerous if not made large enough. The basins are, in effect, small reservoirs having considerable aggregate storage, and failure of an upstream basin may result in progressive failure of lower basins, thus causing a flood greater than might have come from the untreated area. Determination of required basin capacity should therefore be based on careful study of the drainage-area hydrology, and it should include consideration of the possibility of two storms occurring in close succession.

Control of debris by improvement of cover growth and by terracing is generally not applicable to the rugged and rocky San Gabriel Mountains near Los Angeles. Such methods have, however, been reported to be successful along the west face of the Wasatch Mountains in northern Utah (Bailey and Craddock, 1947). The protection of cover growth from fire is, or course, effective in any area.

The foregoing methods of control may require many years to become fully effective. Unless terraces trap all runoff from the drainage area, detritus collected in the natural stream channels will continue to be carried down by floods. Furthermore, as the stream beds are cleaned out and lowered, bank caving is likely to increase. Plant growth usually requires many years to become well established; it can be destroyed in a single fire. In general, where the drainage area is suitable, these methods are applicable if the cost of more positive measures is prohibitive and if immediate control is not necessary.

DROP STRUCTURES

In areas where the bulk of debris comes from the beds and sides of canyons or gullies that have cut through otherwise stable drainage surfaces, a series of drop structures in the channel may be employed to halt debris flow. Drop structures are more generally used in land-conservation projects to halt headward erosion of gullies. They are mentioned here as a method having limited application for debris control.

The function of drop structures for debris control would be to reduce flood velocities and, hence, debris erosion and transportation. Vertical falls and stilling basins at the drops would provide for controlled absorption of excess energy (Morris and Johnson, 1943). The bottoms of the structures should be placed at stream bed with the crests projecting above stream bed. Generally the crest of one drop should be at the elevation of the bottom of the next drop upstream. Initially the structures would form a series of pools. These pools would gradually fill with the finer material carried by the reduced flood-flow velocities until the deposits reached the overflow-crest elevation. Beyond that point, the deposits would continue to build up on increasing slopes upstream from the crests until the original stream slope was approximated. The increasing slope would result in increasing flow velocities and, with the bottom protected from erosion, aggravated erosion would be likely to result along the banks. Thus, if the deposits were not removed, the structures might eventually become detrimental. The useful life of such structures might be increased by providing at each drop a relatively narrow notch or opening that would permit fine materials to be sluiced down the channel instead of being deposited in each pool. Such openings should not, however, be large enough to reduce materially the ponding effect on large flows.

Unless substantially constructed, the structures might fail during a major flow and release all the stored debris, causing a greater debris flow than would result under natural conditions. In very steep canyons (and most debris-producing areas are steep), the cost of treatment with adequately constructed drop structures might be excessive because the drop structures would have to be placed in close succession to reduce stream velocities effectively.

Check Dams and Barriers

Check dams and barriers are somewhat similar, and the distinction made here is purely arbitrary. Check dams usually consist of relatively low barriers constructed across a drainage channel to intercept debris. The storage provided by such construction is usually small, however, and re-excavation frequently impracticable. As a method of debris control, check dams have only limited application. They could be used perhaps to provide immediate relief in connection with methods of watershed treatment already discussed which, in themselves, require several years to become fully effective. As with drop structures, poorly constructed check dams may cause increased damage by collapsing during a flood.

Barriers may be considered as check dams of major proportions. As such, they are designed and constructed as dams. Those known to the writer are located in narrow canyons and are generally concrete-arch structures with overflow lips at the center of the arch. Debris carried into the reservoirs formed by the dams is deposited in the still pools, and the cleared water is discharged over the spillways. Operation is thus entirely automatic. The Los Angeles County Flood Control District has constructed two such structures, and the U. S. Forest Service one, in the canyons along the south face of the San Gabriel Mountains. Storage not occupied by debris has incidental use for flood-peak reduction and water conservation. Original storage capacities of these basins are from 6 to 60 acre-feet. Larger barriers that have been constructed in the Sacramento River Basin are North Fork Debris Dam on North Fork of American River, and Upper Narrows Debris Dam on Yuba River in California, constructed by the Corps of Engineers. The North Fork Debris Dam provides storage for 17,000 acre-feet of debris.

Maintenance of debris-storage capacity behind barriers by excavation is usually not feasible, because the narrow, rugged canyons restrict access of equipment, and because there is usually no suitable adjacent area where the excavated material can be placed and be free from attack by subsequent flood flows. Sluicing of fine materials through suitable openings during periods of low flow will help to maintain storage. However, the sluiced material will be carried downstream by subsequent floods and may cause damage. Consequently, sufficient storage should usually be provided for the entire debris inflow during the life of the structure. Within the limits of storage space available, debris barriers afford positive control of debris. If the downstream channel is steep and erodible, the clear water discharged from the dam will pick up material from the stream bed and carry it to the lower channel reaches. Resulting degradation below the dam may cause caving of banks and undermining of bridge structures. In the lower reaches, the resulting aggradation will generally be somewhat less than would occur under natural conditions, because the dams effect some reduction in peak flow, particularly for small floods. In southern California, where urban and suburban development usually extends up to the canyon mouths and downstream channels are restricted, downstream-channel improvement frequently becomes a necessary adjunct to construction of debris barriers. However, the effect of North Fork and Upper Narrows dams in northern California on downstream regimen is negligible, because the natural sediment load (as distinct from that resulting from mining operations) is relatively light.

Debris Basins

At the mouths of the canyons that drain the precipitous southern face of the San Gabriel Mountains, the Los Angeles County Flood Control District and the Corps of Engineers have constructed 25 debris basins. The approved comprehensive plans of the two agencies provide for eventual construction of about 50 more such basins (see Fig. 2).

Debris basins are like debris barriers in that a pool is provided for settlement and retention of debris while the cleared water is discharged over a spillway. Debris basins are distinctly different, however, in location, design, construction, and maintenance.

The best location for a debris basin is usually at the canyon mouth, in such a position that the basin is outside the canyon for ease of access, but close enough that the inlet can easily be tied to the canyon sides to prevent flood flows from flanking the basin. The site should also include an adjacent area suitable for debris disposal. The basin consists of a bowl-shaped pit excavated in the surface of the debris cone; an embankment, usually U-shaped, constructed from the pit material and located along the two sides and downstream end of the pit; an inlet structure at the upstream end of the pit; and an overflow spillway at the downstream end.

Debris basins are usually designed to hold only the debris estimated to result from a single major storm, and the storage provided is there-

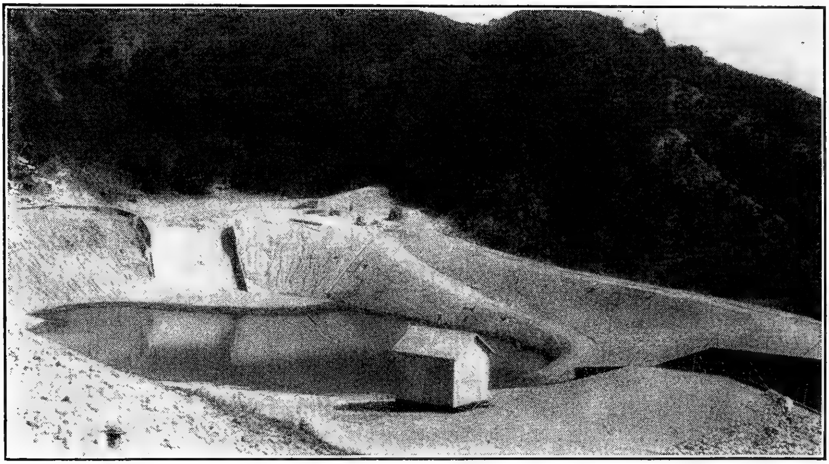

FIG. 2. Typical debris basin, La Crescenta area, San Gabriel Mountains. Hay Canyon debris basin, inlet structure in background, outlet structure at right foreground.

fore considerably less in relation to drainage area than that provided by debris barriers. Because the basin is small, the shape of the basin and the relative positions of inlet and outlet require careful consideration in order that debris will not be discharged over the spillway before all the debris-storage capacity of the basin has been utilized. The inlet consists of a chute or drop structure tied in to the canyon walls and extending from the natural stream bed to the bottom of the excavated pit. The structure serves both to direct flow into the basin and to prevent filling of the basin by headward erosion of the stream bed. The outlet structure consists of an overflow spillway with crest set at the elevation required to provide the desired debris storage.

Debris basins provide immediate and positive control of debris. Because they are designed to store debris from one flood only, accumulations must be removed. As long as the deposited material is removed, however, the basins can control debris indefinitely.

Emergency Debris Basins

Emergency debris control may occasionally be required for highly developed and vulnerable areas lying below a potential debris-producing canyon that is completely denuded by fire shortly before the beginning of the flood season. If insufficient time is available for financing and constructing a permanent debris basin, a large measure of protection against a single flood can quickly be provided by excavating, at the canyon mouth, a pit without inlet or outlet structures. In order to avoid the increased damage that would result from sudden release of stored debris, all the storage provided should be below the natural ground surface. Excavated material should not be used to form an embankment around the pit to increase its capacity; it should be disposed of in a location free from attack by flood flows. Without an inlet structure, the pit may be partially filled by headward erosion during minor flows, and, without an outlet structure, the basin storage may be rendered ineffective if discharged flow creates a gully at the downstream side. These defects can be minimized to some extent by segregating the larger boulders encountered in the excavation and using them to form rock inlet and outlet sills. Gullying at the downstream side of the basin can also be minimized if the basin is excavated along the downstream edge on a contour so that initially, at least, overflow will be in a thin sheet rather than concentrated at one point.

RESEARCH NEEDED

All the described methods of debris control are susceptible to improvement. The control of debris by watershed treatment is probably the least expensive in some areas. However, most debris-producing areas are rugged and semi-arid, and natural plant growth is sparse. Furthermore, in any area, the protection afforded by plant cover is subject to sudden and complete nullification by fire. It is suggested that one field for further study include the discovery and cultivation of plant types capable of achieving dense growth in unfavorable areas; development of inexpensive processes of establishing cover growth; and, possibly, discovery of plant types that would develop a dense surface network of roots that could hold the material in place even if all growth aboveground were destroyed by fire and that could continue to afford such protection until new growth became established.

With the exception of watershed treatment, the methods of debris control discussed involve an estimate of the debris-producing capacity of the problem area. In Los Angeles County, before-and-after surveys of debris deposits in existing basins furnish a guide to debris-production potentialities in adjacent areas that are entirely similar. However, no objective method exists for applying that knowledge to other areas that differ somewhat in their geology, topography, and hydrology. As in all engineering problems, overdesign leads to excessive cost, and underdesign does not produce anticipated benefits and may be dangerous. Thus an objective and practical method for appraisal of debris-producing potentialities based on empirical but well-substantiated factors that reflect the geologic, topographic, and hydrologic characteristics of any area would have considerable value.

Finally, the design of debris-control structures is open to considerable improvement. In general, inexpensive structures are frequently dangerous, and safe structures are usually costly. A wide gap exists between these extremes, a gap that could be closed by the development of structures both inexpensive and safe.

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Chapter 20

SEDIMENTATION IN RESERVOIRS

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This chapter outlines generally the problems of reservoir sedimentation and their significance and considers remedial measures in a broad manner. Covered in some detail are the methods used in measuring sediment deposition in reservoirs. The extent to which the discussion is unbalanced with regard to the various phases of the subject that might be discussed is due to the treatment elsewhere in this symposium of material applicable to reservoir sedimentation, duplication of which is undesirable.

THE PROBLEM AND ITS IMPORTANCE

Sedimentation in reservoirs has become increasingly important because of the ever-increasing number of dams and reservoirs built and continuing to be built during the era beginning in the early 1930's. Particularly is this true for large reservoirs, many of which are for multiple purposes. Such reservoirs may be so affected by sedimentation that one or more of their major purposes, such as flood control, navigation, irrigation, water supply, hydroelectric-power production, may be seriously curtailed or even cancelled. Minor uses such as recreation are also affected by reservoir sedimentation. Sedimentation in the many relatively small reservoirs scattered throughout the country which furnish water supply for cities and towns may seriously affect the available carry-over water supply and necessitate abandonment and new construction at considerable cost.

For reservoirs proposed for future construction, sedimentation is particularly important in those areas where streams carry heavy sediment loads. In such areas, rates of reservoir sedimentation must be estimated accurately in order that the useful reservoir life may be determined. These determinations may be basic in evaluating the economic feasibility of projects on heavy silt-bearing streams.

FACTORS THAT INFLUENCE RESERVOIR SEDIMENTATION

The amount of silt that is brought to a reservoir on any stream is influenced by the watershed characteristics above the reservoir, such as the geology, types of cover, and the climate that prevails over the area. The amount of sediment that remains in the reservoir is a function of the retention time of the water in the reservoir. The life of a reservoir is dependent on the ratio of the reservoir capacity in acre-feet to the watershed area in square miles. Where this ratio is small, the life of the reservoir will be relatively small. Where the ratio is large, with other conditions being the same, the life of the reservoir will be correspondingly long.

In the design of many reservoirs, provision is made for dead storage and live storage. The former ordinarily is considered to provide space for the deposition of sediment for a considerable period of years. It is important in the life of a project to determine whether sediment deposits in the dead-storage space or whether it deposits in the live space and thereby encroaches on the purposes for which the reservoir was built.

The level at which a reservoir is operated is an element of significance in reservoir sedimentation. Some reservoirs, usually single-purpose, are operated with relatively constant levels. Multiple-purpose reservoirs that utilize storage space jointly at different seasons of the year are operated at other than constant levels and with a range in reservoir elevations dictated by the various purposes for which the reservoir was built. This variation in water level in a multiple-purpose reservoir is significant in the deposition of silt in a reservoir and also in the movement of silt through the reservoir. At the higher reservoir elevations the silt is first deposited in the live storage space, but, as the reservoir is drawn down and succeeding storms occur, this sediment is flushed down into the lower elevations of the reservoir and eventually, after a number of cycles, is likely to find its way into the portion of the reservoir originally provided for dead storage.

In a series of reservoirs, such as, for example, that constructed by the Tennessee Valley Authority on the Tennessee River and its tributaries, the deposition in succeeding downstream reservoirs is more and more influenced by the depositions that occur in the upstream reservoirs. Naturally, the first upstream reservoir traps the greatest amount of sediment, and only the finer material passes on to the next downstream reservoir. The downstream reservoirs then receive a certain amount of material from each upstream reservoir and in addition the contributions from the local drainage areas directly tributary to each reservoir.

MEASUREMENT OF SEDIMENTATION IN STREAMS

Accurate measurements of sediment loads in natural streams are essential to estimating the useful life of any proposed reservoir. Measurement of volume of silt deposited in a reservoir is important to determine the rate at which sediment is being deposited and the locations where the deposits are being made. The latter also provides a check on the computations that may have been made on the basis of measurements of suspended sediment loads before the construction of the reservoir.

The science of accurate measurement of sediment loads in streams is relatively new. Until some ten years ago engineers throughout the country who were concerned with sedimentation problems largely devised their own equipment for sampling streams and carried on sampling programs, each according to his own ideas. This led to both inaccuracy and non-uniformity of results with little basis for comparison or dependable utilization. To remedy this situation, government agencies interested in sediment problems formed a group that sponsored a research project at the Iowa Institute of Hydraulic Research. This project notably developed standard sediment samplers for use under different conditions of stream flow. These samplers have since been adopted and are being used by practically all government agencies. The series of publications issued by this project is a monumental contribution to the science of sediment measurement (Iowa Institute of Hydraulic Research, Nos. 1–5, 7–9). Figure 1 shows one of these samplers.

In the measurement of the suspended-sediment load of streams, the program of measurement must be carefully planned and executed. The volume of sediment carried varies with stream flow but does not bear a constant relationship to the quantity of water flowing. In low water, the sediment volume is usually small, but during rises in the stream the amount of sediment increases rapidly. Ordinarily the peak-sediment load will occur prior to the peak stream flow discharge. To determine the volume of sediment carried during rises in stream flow, rather frequent sampling must be carried out. The amount of the sediment will depend on the season of the year, the condition of the land in the watershed with respect to cultivation or other factors that influence erosion, intensity of rainfall, and other hydrologic factors that alter the sediment load with the discharge.

The samplers developed by the cooperative federal project utilize a pint bottle for obtaining the sediment samples (Iowa Institute of Hydraulic Research, Nos. 5, 8). The samples taken on any stream are analyzed in a laboratory to determine the amount of sediment carried

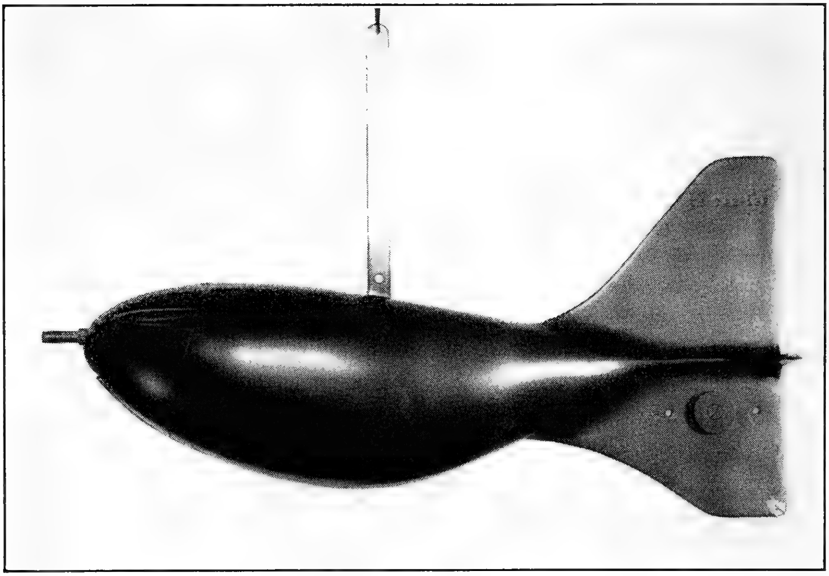

Fig. 1. Modern sediment sampler used in open streams. The sample flows through the calibrated nozzle into a pint bottle inside the body. Sampler is hinged to permit removal of bottle.

by each sample (Iowa Institute of Hydraulic Research, No. 4). On the basis of the quantity determined by the laboratory analysis, the amount of silt carried by the stream can be computed.

In addition to the amount, the size of the particles of the sediment is important (Iowa Institute of Hydraulic Research, No. 7). The size of the sediment particles influences the location in the stream cross section where the sediment is carried and is an important factor in the deposition of the sediment in a reservoir. Fine-grained material, for example, will be carried farther into a reservoir and deposited nearer the dam than coarse-grained material, which tends to deposit near the upper end of the streams that bring it into the reservoir. Research has developed the bottom withdrawal tube for determining the size of particles (Howard, 1948).

MEASURING SEDIMENT IN RESERVOIRS

Reservoir-sedimentation surveys determine the amount of material deposited in a reservoir and show where the deposits exist within the reservoir. Successive surveys provide data for tracing the movement of sediment through or within a reservoir. Primarily, the practical objective is to obtain accurate information on which to base estimates, first, of the length of time that will elapse before any of the purposes of the reservoir are interfered with and, second, of the total useful life of the project (Fry, 1948).

Volumetric measurements of sediment in reservoirs are made by soundings taken to develop the configuration of the reservoir sides and bottom below water surface at the time of the survey. Deposits above water level are measured by bank sections obtained by ground surveying methods.

In small reservoirs and in special situations in larger reservoirs, sufficient soundings are taken below water and elevations are taken above water to permit drawing of contours for the reservoir. Computations of the volumes of storage at different elevations based on successive surveys will indicate by the reduction in storage the amount of deposition at any elevation (Eakin and Brown, 1939).

In large reservoirs, the contour method is not generally applicable because of the time and expense that would be entailed. In these reservoirs, volumes are determined by soundings made along ranges established usually at the time the project is built (Fry, 1948).

Layout of Ranges

Before a reservoir is filled, silt ranges should be carefully located on a map in sufficient number and in proper locations so that soundings on these ranges will furnish the necessary data for computation of silt volumes. Range locations should consider important local tributaries and their probable sediment characteristics. A closer spacing of ranges is usually more desirable in the upper and shallower end of the reservoir than in the lower and deeper portion. The width of reservoir is important. If there is a system of reservoirs on one stream such as that on the Tennessee River, the location in the system with respect to protection from upstream reservoirs may be significant. In reservoirs subject to considerable drawdown, closer spacing of ranges within the drawdown reach is desirable, as the deposition and movement of silt throughout this range are greater than in other parts of the reservoir.

Base Survey of Ranges

After ranges have been located on the map, elevations must be taken along each range to give a cross section of the reservoir at each range. The ends of the proposed ranges are first monumented in the field with a permanent type of monument adequately referenced so that they can be found several years later.

In canyon-type reservoirs such as those of Norris and Fontana reservoirs in the Tennessee Valley, where the sides of the valley are steep and the water depth is great, an accurate profile should be taken by surveying along each range prior to the filling of the reservoir. This base profile before filling is preferable to a profile by echo sounding immediately after filling, although, in reservoirs of very rugged topography, echo sounding may be the only feasible method for obtaining the original section. If there is timber along the line of the silt range, this should be cleared if it is intended to sound with a lead line in the future. Where echo-sounding equipment is to be used for subsequent surveys, the clearing is not essential.

In reservoirs located in terrain where the topography is less steep, the depth of water is less and the width is greater than in canyon-type reservoirs, it is much more economical to determine the profile along the silt range by soundings after the reservoir is filled than it is to do so by ground-survey work prior to filling. Bank work to supplement the sounding surveys along the ends of the range may be necessary to develop the section above the existing stage of water when the sounding is done.

Subsequent Reservoir Surveys

The surveys either prior to or immediately after the filling of a reservoir furnish the base for comparison with data from resurveys made after an appropriate interval of years following closure of the reservoir. Such resurveys enable determination to be made of the volume and rate of reservoir sedimentation and the manner in which the sediment is deposited and moves through the reservoir.

Since resurveys usually must be made with water in the reservoir, one form or another of sounding is used. For very shallow water depths, a sounding pole equipped with a base plate may be used. Beyond the range of a sounding pole, the general practice until the past few years has been to make soundings by conventional lead-line methods. Although the lead line will still be useful for surveys of reservoirs where more modern methods are not available or justified economically, on large projects or reservoirs, future soundings will be made by supersonic equipment.

Supersonic Sounding Equipment

Although fathometers using the general principle of supersonic sounding have been in use for more than 25 years, this type of equipment was improved and developed during World War II so that it is now the most practical and economical means of making soundings in reservoirs or other bodies of water. This equipment determines water depths by utilizing supersonic-sound-pressure waves and precision timing. There are two principal units and essential accessories. One unit is a projector, the function of which is to transmit sound-pressure waves to the reservoir bottom and to receive the reflected waves. The second unit is a recorder electrically connected with the projector which, by electronic and mechanical means, gives a permanent and continuous record on a calibrated chart of the depths of water through which the sound waves are sent. A 12-volt storage battery powers the equipment. Total power consumption approximates 120 watts. (See Fig. 2.)

With this equipment, rapid, automatic determination of depths of water and observations of the configuration of the bottom of the reservoir are obtained. In operation, the power switch is turned on, sending electrical impulses at a frequency in the supersonic range to the transmitting projector, where each impulse is converted to a sound-pressure wave. This wave is projected downward through the water to the bed of the reservoir, whence it is reflected upward to the receiving projector. The reflected sound-pressure wave is converted in the receiving projector to an electrical impulse which, in turn, records on the chart. The wave is very accurately timed in units of depth for the round trip. The elapsed time interval is converted into feet or fathoms on the basis of the velocity of sound in water for direct recording of depths of water on the chart. The chart speed is 1 inch per minute. For the type of equipment being used in the Tennessee Valley, depths of water are recorded in feet up to 200 feet and beyond that depth in fathoms up to 200 by a change in scale of the equipment. Soundings in feet are recorded at the rate of 200 per minute and in fathoms at the rate of 33⅓ per minute. Soundings are recorded on rectilinear or curvilinear charts, depending on the design of the equipment. Both types of charts have their advantages.

On reservoir investigations, the echo-sounding equipment is operated from a boat suitable for carrying the equipment and operating personnel.

The hydrographic party for reservoir-sedimentation investigations consists of four to five men specially trained for their duties. These are

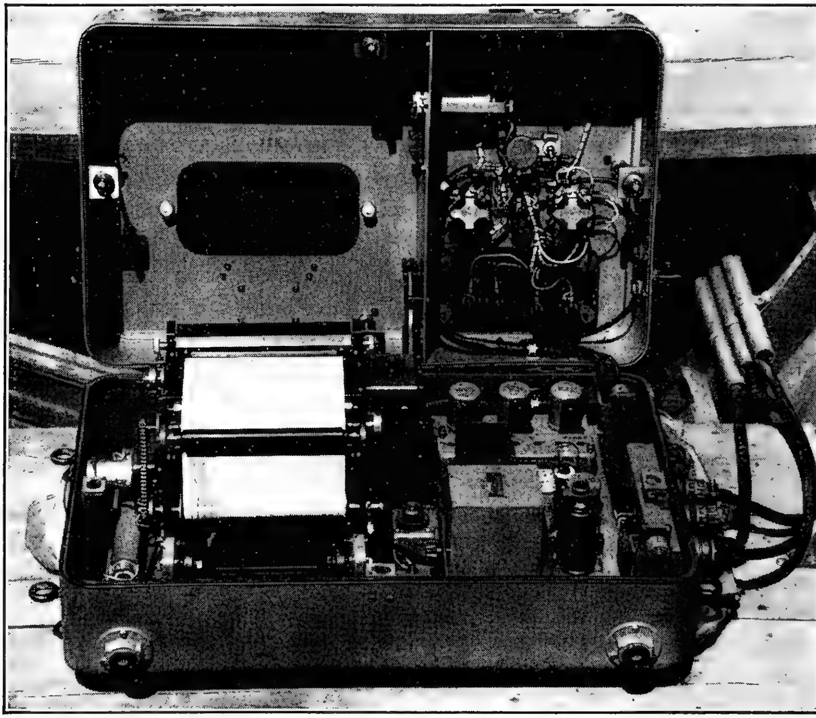

FIG. 2. Echo sounder showing chart.

a chief hydrographer, an instrumentman, a boat operator, a sounding-recorder operator, and a distance-wheel operator. It is desirable for the recorder operator or another man in the party to have some knowledge of radio and electronic circuits.

OTHER EQUIPMENT

Equipment is designed to provide complete mobility and to permit the entire outfit to move readily from a reservoir in one part of an area to that in another area perhaps a hundred or more miles distant. Automobile equipment consists of one sedan, a ¾-ton covered truck with four-wheel drive, and a boat trailer. The boat that carries the equipment is 20 feet long and has a beam of 5 feet and a draft of about 1 foot when loaded. (See Fig. 3.) The boat is especially fitted with a well in the center through which the sound-wave projector operates. Three outboard motors are used, two of 16 horsepower each and one of 10 horsepower.

The echo-sounding equipment includes the sounding recorder, projector, storage batteries, and depth-checking bar. The projector is of the outboard type which is designed to be operated by being swung over

Fig. 3. Sounding boat on reservoir survey. The man in the bow maintains shore contact with a hand radio, the man with the flag operates the echo-sounding recorder, the man standing operates a device that measures distance from shore by a taut piano wire, and the man in the stern operates the outboard motor that powers the boat.

the side of the boat and positioned below the water line for observations. However, with a boat of the size used for purposes of mobility, it has been found desirable, from the standpoint of the most satisfactory and safest loading of the boat, to operate the projector from a well centered in the hull. A simple lowering device positions the projector at the operating depth of 1 foot below the water surface. The heavy storage batteries, weighing about 165 pounds, are charged in place on the boat by a small motor generator.

One of the chief pieces of equipment is the circumferential-type distance-measuring wheel devised by TVA's Chief Hydrographer, E. H. McCain. The distance-measuring apparatus consists of the drum of a Ford automobile wheel on which is wound 2,500 feet of piano wire 0.039 inch in diameter. The wire leads from the drum over two sheaves to a fixed pivot point on the bank from which measurements are taken. The second sheave is made of casehardened steel to maintain a fixed rim diameter and operates a three-digit counter that indicates the distance of the boat from the pivot point.

The party is equipped with transit, plane table, 200 feet of steel chain, chainman's plumb bobs, signal flags, Abney level or clinometer, machete, hand axes, and iron pins.

One of the most useful pieces of equipment is a Walkie-Talkie radio which enables the boat party and the instrumentman on the bank to maintain conversational contact with one another, thereby eliminating hand signals and misunderstanding.

Sounding Range

Prior to the actual sounding, ranges should be located and marked by a red or white flag, about 2 feet square, on a stick behind the silt-range monument. Red is used where the background is light, white where it is dark as seen from the water.

If the hydrographic party moves up to a range in the boat, the boat lands on one bank. The distance from the monument to a point on the shore is measured with the steel tape and the vertical angle taken from that point to the range monument by the hand clinometer. The transit is set up over the point so located. The boat with the other members of the party then crosses to the opposite bank in order that, during sounding, the boat operator will be facing the instrumentman. Here a point is set on range about 5 to 8 feet above the water where an iron pin is driven into the ground. The distance from this pin to the range monument on that bank is measured, and the vertical angle is taken. The distance from the pin to the distance wheel on the boat is then measured. The end of the distance wire is secured to the iron pin and the counter set to read the distance from the pin to the wheel. The projector is lowered, the chart operator turns on the sounding recorder, and the boat moves across the river on the range at a speed of about 3 miles per hour. The transitman keeps the boat on range by giving directions over the Walkie-Talkie to the boat operator, who wears headphones connected to the radio on the boat. At the end of the run, the distance from the boat to the instrument is taped.

The recorder is equipped with a fix button which, when pressed by the operator, prints a line on the moving chart. At intervals of approximately 25 or 50 feet, the distance-wheel operator calls out the distance, the chart operator pushes the fix button and notes the distance on a sheet of paper. These distances are transferred to the chart immediately on the completion of the range.

On the completion of the sounding of a range, the instrumentman boards the boat, and the boat retraces the range in order to rewind the piano wire on the distance wheel. The rewinding is done by a small motor at 400 feet per minute. At the bank, the end of the wire is released, the iron pin is pulled, and the party heads for the next range.

The temperature of the water must be taken into consideration in the operation of echo-sounding equipment. At the beginning of a day's run and at other periods, if there is much change in depths of the reservoir, a check is made with the sounding recorder by submerging a steel bar hung from chains on either end to known depths below the water surface and recording the echoes therefrom. Successively lowering the bar by known intervals of 10 feet gives the depths, which are recorded on the chart, and the corrections that must be made to reduce the chart depths to true depths. The bar check is considered accurate to a depth of about 100 feet. For greater depths, corrections are made on the basis of water temperature. For example, in a survey of Hiwassee Reservoir, temperatures at 100 feet of depth were 42° F., and soundings were corrected for this condition. Corrections for salinity must be made where it exists.

As in any type of sounding, there is the problem of the character of the surface of the bottom where the soundings are taken. The possibly unconsolidated nature of relatively new deposition introduces difficulties of interpretation and application of the soundings. The solution for this problem lies in methods for determination of density of materials in deep water which are separate from the soundings themselves.

Determining Position on Range

For ranges up to a length of 4,000 feet, position on range is determined with the distance wheel. For ranges longer than 2,000 feet, the party works first from one bank and then from the other to a distance of about 2,000 feet. In establishing ranges initially where the length exceeds 2,000 feet and on resurveys for ranges longer than 4,000 feet, location on range is determined by cutting angles with a plane table from the bank. If distance-wheel equipment is not available, position may be determined in the manner described in the succeeding paragraph for long ranges.

Some reservoirs have expanses of water as wide as 2 to 3 miles. These are beyond the limit of the distance wheel for position measurement. For ranges of such great length, two instruments are used on the bank. One is a transit to keep the boat on range, and the other is a plane table to locate the soundings by cutting in horizontal angles. The plane-table point is located as far from the end of the range as the range is wide, or perhaps on an island in the lake if one is available. Plane-table points for a day's sounding are always chosen before the day's work is begun. For this type of work, the Walkie-Talkie radio instrument is invaluable to increase efficiency of the party and speed up the work. Both men on the bank are equipped with Walkie-Talkies, and a third instrument is used on the boat. As the distance wheel is not used on long ranges, the wheel operator becomes the radioman on the boat. To obtain best radio conditions, he takes a position on the bow of the boat removed from the recorder mechanism and motors. The transitman uses his Walkie-Talkie to keep the party on range. The plane-table man follows the sounding boat through the alidade and cuts in position at each sounding by horizontal angle on the plane-table sheet whenever the sounding operator indicates a fix by waving a flag. Flags are alternated, four white flags and one red being used to provide a check for the plane-table man in observing positions and plotting them on his sheet. After the boat has completed its run to the opposite bank, contact with the plane-table man by Walkie-Talkie makes certain that he has obtained all the necessary data. The plane-table man in this case has a separate small boat and proceeds independently to the plane-table point from which he will cut in sounding positions for the next range. Meanwhile the main party also proceeds to that range. Contact is again established on the Walkie-Talkie before the new range is started. It is possible to carry on work in this way, perhaps for a whole day, without the main sounding party even catching more than a glimpse of the plane-table man.

Surveys of Deltas or Other Areas

In detailed surveys where it is desired to measure the volume of material brought in by tributaries and deposited as a delta, or to determine accurate bottom contours in a zone several hundred feet in radius, the radial-sounding method is highly efficient. An expert boatman is essential for this type of work, as the boat must be held closely in position and must be handled skillfully in order not to break the distance wire. A pivot point is located on the bank adjacent to the area to be surveyed, and a plane table is set up over this point. The distance wheel is initially set at a fixed distance of 25 feet from the pivot point. The pivot point is placed high enough above the water to keep the distance wire out of the water, and, for distances up to 300 feet, correction for the inclination of the wire is set on the distance wheel.

Starting at the bank, the boat swings in an arc, keeping the distance wire taut until the boat reaches the bank 50 feet distant from the starting point. The distance wire is then extended another 25 feet to a total of 50 feet from the pivot point, and a reverse arc is run if the sounding is taking place in still water. If there is appreciable current, the soundings must all be made in arcs swinging with the current. As the boat proceeds along each arc, the chart operator presses the fix button and at the same time indicates to the plane-table man his position by dropping a flag, using the red and white flag system previously described. By successively increasing the radial distance, the desired area is covered completely and accurately. The plane-table man prepares the plane-table sheet before setting up by drawing arcs at 25-foot intervals. As he follows the sounding boat around each arc, he marks the position on each arc on the plane-table sheet where a sounding fix is indicated.

Density of Deposited Material

In the utilization of the underwater sounding data from reservoir resurveys, the density of the deposited material and the degree of consolidation are particularly important (Iowa Institute of Hydraulic Research, No. 9).

Density of consolidated sediment should be known in order to translate measurements of sediment moving in natural rivers into volume that will be occupied by that sediment in a reservoir built at that location. The state of consolidation is important in order to compare volume occupied by sediment at any time with the volume that will be occupied after ultimate consolidation takes place. Unless the degree of consolidation at the time of a survey is known, erroneous conclusions may be drawn from the data with respect to rate of silting and useful life of a reservoir.

ECONOMIC SIGNIFICANCE OF RESERVOIR SEDIMENTATION

Reduction of storage in reservoirs that serve vital regional or community purposes may eventually result in impairment of the functioning of the reservoir to the point where it will have a disturbing effect on the economic life of the region or community. Stevens (1946) illustrated this point when he sounded a warning to the interests dependent on storage of water in Lake Mead that the useful life of the reservoir would be relatively short owing to the filling of the lake with silt. More recent accurate measurements of depositions in Lake Mead give the lake a considerably longer life than Stevens anticipated. However, the fact remains that unless protective measures or other construction is undertaken on the watershed upstream from Lake Mead, the usefulness of that great lake will within a few generations be seriously impaired. The effect would be a progressive return to the run of river conditions of water supply which existed prior to the construction of Hoover Dam, with consequent very large economic losses to irrigation, power production, flood control, and water supply.

The economic losses that would result from the catastrophe of the filling by silt of such a great reservoir as Lake Mead would be very large. This is probably the most spectacular example to be found within the United States. However, wherever reservoirs are built on streams that carry significant volumes of silt, some degree of economic loss must be anticipated.

Important water losses may occur as a result of the effects of sediment deposition in reservoirs, particularly in arid and semi-arid regions. Evaporation increases because of the relative increase in exposed water surface for the same volume of water storage. Transpiration from vegetation growing on sediment deposits at the heads of reservoirs may consume large quantities of water. For example, it has been estimated that the annual loss by transpiration by vegetation growing on deposits at the head of the reservoir formed by Parker Dam on the lower Colorado River is 400,000 acre-feet (Maddock, 1948).

The loss of use of a good dam site because the reservoir fills with silt is a serious economic problem. Good dam sites are scarce, and the first site selected and used may exhaust the opportunities for economic development on a stream or in an area. If the reservoir is destroyed by silting, the possibilities for building replacement projects are usually limited or non-existent.

REMEDIES FOR RESERVOIR SEDIMENTATION

What can be done to cope with the problem is a question that can be answered only for each specific situation. Because the silt originates in the watershed tributary to a reservoir, the most obvious point to prevent silt from being carried into a reservoir is the watershed itself. A good vegetal cover on a watershed is the best preventive of sedimentation, and it assures long life for a reservoir. For example, the Fontana Reservoir of the Tennessee Valley Authority on the

Little Tennessee River is estimated to have a life of nearly 4,000 years before it will be filled with silt. This long life is due primarily to the watershed having a cover of trees and other vegetation. On the other hand, a small reservoir above a diversion dam on the Ocoee River located below a denuded watershed, because it traps the sediment eroded from the denuded land (Tennessee Valley Authority, 1949b), is estimated to have a useful life of not more than half a century, at which time certain operating advantages derived from the reservoir will be lost, although the main purpose of the project, to divert water, will not be affected.

The success of watershed protective measures depends both on the climate and on the management of the land in the watershed. If either of these is not favorable, reservoir silting is certain to be aggravated. Improvement of the watershed cover is extremely difficult and may be practically impossible in those climatic regions where precipitation occurs only occasionally and then in very intense storms (Peterson, 1948). In such watersheds, sod-forming grasses are uncommon in nature, and evidences of geologic erosion are on every side.

Once sediment has been deposited in a reservoir, disposal is extremely difficult and practically impossible. In isolated cases, density currents have carried some silt through a reservoir (Bell, 1942; U. S. Department of Interior, 1949). However, the effect of density current flow on the amount of sediment deposited within the reservoir is necessarily small. On some projects, it is possible to carry silt through a dam by means of sluices through the structure. Ordinarily, however, this is not feasible, because to reduce materially the sediment content of a reservoir would require a long period of sluicing during which the reservoir would be out of use. Dredging in a few special cases may be resorted to, but this method is not generally applicable.

Perhaps engineers should pay more attention in the original design to provide for eventual sluicing of silt through a dam. At the time when the amount of sediment deposited in a reservoir becomes sufficient to interfere seriously with the purpose or purposes of that reservoir, it might be practical to abandon the uses of the reservoir and open sluices and carry away through the dam the silt that has been deposited. How long this would take would depend on the amount of silt, stream flow, or other local conditions. But it would probably be cheaper to carry out such de-silting operations over a considerable period of time, even for rather large reservoirs, than to construct entirely new reservoirs. Looking considerably ahead, if conditions warrant, when many reservoirs now constructed become silted to the point of seriously impaired usefulness, future generations may find it necessary to remove portions of the existing dams and permit sediment to pass on downstream over a period of, perhaps, several years. After the desilting has taken place, the portion of the structure could be replaced and the reservoir restored to something like its original life.

FUTURE RESEARCH NEEDED

Much additional research is needed in the field of sedimentation in its application to reservoirs. Probably most of this will be done by federal agencies, which are most concerned with sedimentation in reservoirs built by the various agencies. There is also a wide field for research investigations by non-federal agencies in connection with such matters as determination of the laws of sediment transportation and particle-size determination.

Samplers for suspended sediment have been developed to an advanced stage, but satisfactory methods and equipment for bed-load measurements are still a fertile field for exploration.

In reservoir-sedimentation surveys, there is opportunity for further improvement in echo-sounding equipment. In this field, probably the research most needed is for the development of practical and economically feasible methods for determining horizontal positions of reservoir soundings by electronic methods.

Determination of the density of deposited sediments and the laws of consolidation of materials under conditions that exist in reservoirs offer opportunity for research, because the density and consolidation of material in a reservoir are so important in determining the volume that will be occupied by sediment. Improved equipment is needed to sample deposited sediments satisfactorily. Such equipment should be capable of obtaining samples through 20 or more feet of sediment under a depth of water of perhaps as much as 50 to 100 feet.

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Chapter 21

PROBLEMS OF IRRIGATION CANALS

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CAUSE OF SILTING

Irrigation canals are the waterways by which water is transported from a source of supply, such as a reservoir or river, to the area on which it will be used for irrigating the land for agricultural purposes. Laterals are small irrigation canals that take the water from the principal irrigation canals and carry it to the individual farms. Irrigation canals and laterals may be either open ditches or closed conduits, depending on local conditions. Open ditches may be lined or unlined, depending on whether losses by seepage are sufficient to justify lining with impervious materials.

An unlined irrigation canal does not differ greatly from a river or navigation channel as far as problems of sedimentation and erosion are concerned. Like the navigation canal, an irrigation canal is designed to have certain hydraulic properties which are obtained by constructing the canal to a predetermined cross section and grade. Just as a river is subject to aggradation or degradation, so a canal is subject to aggradation or degradation if its hydraulic properties are destroyed through sedimentation or erosion.

Sedimentation of canals—and canals in this instance and hereafter should be understood to mean both main or principal irrigation canals and irrigation laterals—is defined as the uncontrolled deposition of silt in the canals. This silt may be from sloughing of the canal banks; it may be waterborne, from erosion of sections of the watershed contributing to the water supply; or it may be local erosion from lands adjacent to canals. Problems of sedimentation in irrigation canals are, therefore, similar to the sedimentation problems to be found in other types of canals, reservoirs, and in natural waterways.

Sedimentation of irrigation canals creates two problems: (1) how to reduce or eliminate sedimentation, and (2) how to reduce the cost of removal. The first is of prime concern to engineers and geologists; the second chiefly to engineers.

Before attempting an analysis of these problems to see what can be done about them, it is desirable to consider the effects of sedimentation of canals in order that the practical application of the problems can be understood. There are five major effects of canal sedimentation. The first three of these can be classed as adverse; they are: (*a*) changes in hydraulic properties of the canals; (*b*) providing a base for weeds and water plants; (*c*) increasing the maintenance costs. Two of the effects can be classed as favorable, and they are: (*a*) sealing of crevices and porous areas in the canals; (*b*) provision of a source of fertilizer to lands beyond the farm turnout.

A brief discussion of each of these effects is important to an understanding of the problems and the solutions sought. It is apparent that deposits of silt in a canal will change its hydraulic properties. If the grade is changed, the velocity of the canal is altered. If the cross section is changed, the area of the canal is changed. Both changes affect discharge or carrying capacity. Almost always the velocity and cross section are reduced so that the net effect is cumulative; that is, the volume of water carried by the canal is reduced.

For example, examine the effect of six inches of silt deposit on the bottom of representative canals. For a canal with a width of 6 feet and a depth of 3 feet, $r = 1.86$, $n = 0.0225$, $s = 0.00040$, $v = 1.95$, the design capacity Q is 52.7 cubic feet per second. With a silt deposit of 6 inches, Q reduces to 37.6 cubic feet per second, a loss of 28.7 percent in carrying capacity. Similarly, 6 inches of silt will reduce the initial capacity of a larger canal from 126 to 100 cubic feet per second, or 20.6 percent, and that of a main canal from 458 to 400 cubic feet per second, or 12.7 percent.

It is evident from these simple computations that the control and removal of silt from irrigation canals are important, particularly in the smaller canals. If the silt cannot be removed from the water before it enters the canal system, ways must be found to remove the deposits as cheaply as possible from the canals. If the canals are not kept relatively clean, sufficient irrigation water cannot get through, and crop damage results. But, if the expense of removal is too great, it will exceed the capacity of the farmer to pay, again leading to economic failure. The cost of cleaning canals balanced against the cost of desilting works will often show that the desilting works are a cheap investment.

Deposits of silt provide a fertile base for weeds and water plants. Irrigation canals are abundant sources of noxious weeds which, with a little nourishment, flourish prolifically. Fine soil material, which comprises the sedimentation found in many irrigation canals and deposits on the banks of canals, particularly along the water line, provides excellent seed beds. Weed seeds float down with the irrigation water, sometimes coming from remote places in the watershed, or are blown in from adjacent fields and are deposited in this fine material. With moisture from the canals the seeds sprout, and a weed infestation on both the canal and adjacent farms is started.

Water weeds are of two types: submerged and emergent. Examples of the first are sago pondweed, horned pondweed, waterweed, and coontail; examples of the second are cattails, tules, and watercress. For support these plants depend in large measure on soil in the side or bottom of the canals. Silted areas of the canals are an ideal place for these plants to live in.

Removal of silt to restore the canal to its original hydraulic properties and to destroy the weeds and water plants it supports is expensive. The cost of removing silt represents a portion of maintenance costs directly chargeable to sedimentation. Other costs, such as depreciation of equipment and possible crop reductions or crop losses due to inability to deliver adequate water, are less tangible costs but are also involved. A further discussion of costs is given in subsequent paragraphs.

On the favorable side, sealing of canals by silt reduces seepage losses. Many canals are built through soils of high porosity; that is, sufficient water can seep through the wetted perimeter to cause a measurable loss of valuable irrigation water. Deposits of silt in the bottom and sides of the canal often reduce these losses to negligible amounts. Modern irrigation engineering, however, requires that sealing of porous areas by silting should be done as a planned engineering operation rather than be allowed to occur as an act of nature with no control over its rate or period of action.

Silt carried in irrigation water, not deposited in the canals, usually passes on to be deposited on the farms. Test measurements show that the portion of silt carried through the farm turnout may be as high as 50 percent of the silt content at the head of the canal system. On the farms, with the reduction in velocity, silt is deposited at the head ditches, causing sedimentation problems there. Where not trapped in the head ditches, the silt is carried on to the crop land itself, where it acts as a fertilizer to the crops being grown.

Some idea of the effect of silt seals in irrigation canals can be gained from the experience of the Yuma project in Arizona on the lower reaches of the Colorado. Records of the project show that for the 10-year period 1927 to 1937 an average of 13.5 percent of all water delivered to the Valley Division was recovered in the drains and pumped to Mexico at the International Boundary. Beginning in 1938, there was a marked increase, to 18.9 percent, with a continued increase to 24.5 percent in 1947. The most likely cause of the increase is seepage from unlined canals, arising from erosion of the old silt seals by the change in silt content of the water supplied from the Colorado after the closing of the gates at Hoover Dam in 1935. The silt content changed from finely divided soil particles to coarse granular material, picked up from the river bed below Boulder Canyon.

That silt is a fertilizer is generally recognized. The periodic overflowing of the great rivers of the world has long been a source of nutriment to the flooded lands—whether they were in the valley of the Nile, Mississippi, or Missouri. Only on silt-free rivers like the Columbia is the fertilizing feature not evident. Facts and figures are not readily available, but it is known that removing silt from irrigation water formerly having a high silt content results in forcing the affected farmers to increase their use of commercial fertilizers to maintain crop yields.

CONTROL OF SILTING

With this understanding of the effect of silt in irrigation canals, the problems to be considered are restated: (1) How can the inflow of silt into canals be reduced or eliminated, and (2) how can the cost of removal of silt be reduced?

The reduction or elimination of the inflow of silt into the canal must go back to the sources of silt, which are the watershed, canal-side lands, including tributary waterways and sloughing of the canal banks.

The steps that could be taken to overcome the first problem are reviewed in the same order. To reduce the inflow of silt or to eliminate it from the watershed involves a number of actions.

As a first step, the sources from which the silt is originating must be determined. This requires a survey of the watershed which, for some irrigation areas, may involve large areas of semi-arid desert, mountainous, and completely arid desert country. Aerial reconnaissance maps are the best source of information, followed by close-order aerial photography of the principal areas contributing silt, and, sometimes, even plane-table surveys of the chief areas of erosion which have been isolated by the aerial surveys.

When surveys have isolated the sources of silt, it becomes the personal problem of the geologist and the engineer. A determination must be made of the class of material being eroded (rock, soil, sand, etc.), cause of erosion (wind, rain, excessive irrigation, etc.), the geologic history, and probable geologic future. Accompanying the report of the geologist there should be an engineering report citing possible plans for controlling or eliminating erosion by dam construction (major or check dams), channel controls, or other means. The engineer's report must then estimate the cost so that it can be balanced against downstream benefits to determine whether the work is economically justified.

It may be well to point out here that watershed surveys and cost-benefit reports are seldom undertaken to improve sedimentation of canals. Usually such surveys are undertaken to determine flood-control benefits. With the increasing cost of silt removal from canals more attention should be given to the condition of watersheds than heretofore.

Ownership of the watershed is a major factor in any solution. In the western states a watershed that contributes to the silt of the irrigation systems is most likely to be in federal ownership. However, this ownership may very properly be divided among several bureaus of the Department of Agriculture, the Department of the Interior, and war and defense agencies. In addition, there is a possibility that large private ranches may be interspersed among the federal tracts. If erosion is occurring on these lands to a serious extent, a cooperative effort among all owners, public and private, is essential to overcome the problem.

The development of a cooperative agreement and the supervision of its operation should be the responsibility of the principal landowner involved or of the government agency concerned with that type of activity. Adequate funds are important, as lack of funds is the primary reason why so little work has been done in this field in the past. Congress regularly appropriates funds for soil-erosion control on both private and public lands, and the wise application of these funds to treatment of watersheds contributing silt inflows into irrigation systems can be a material factor in reducing or eliminating such silt. Good geologic and engineering reports can do much to insure the availability of necessary funds.

In the same way, major contributions of silt from lands adjoining irrigation systems should be isolated and examined. Aerial photography is not ordinarily required, as most lands are under cultivation and sources of silt are found in wasteways, drain ditches, or natural creeks that are carrying waste or storm water from land being eroded.

Natural stream channels, if overloaded by irrigation waste water or runoff from storms, may become major sources of silt through erosion of the channel cross section. In the western United States, dry land subject only to natural precipitation may change its physical characteristics under irrigation and the rise of the water table. Geological reports are invaluable in appraising the probable erosion action of land proposed for irrigation or being irrigated for the first time. Eroding channels, which may have a major effect on increasing sedimentation of irrigation canals lying below, are often a difficult problem to overcome, not because of lack of information but because of lack of responsibility and funds. Elimination of erosion of these waterways is not ordinarily the responsibility of the organization that operates the irrigation system. Community action or a soil-conservation district may be required to begin corrective measures. Again good reports of ground conditions are essential. Elimination of the silt contributed from these sources then becomes largely a matter of having adequate funds to control or eliminate the erosion, and this may be accomplished by redesign of the waterway, by placing of lining or riprap, or by substituting an alternate waterway not subject to excessive erosion.

Bank sloughing is a condition that contributes silt within the canal. This condition is likely to occur in any area where the velocity of the water exceeds the original design limit so that the water contains sufficient power to cut into the material forming the banks of the canals. Such action will also occur where the bank material is less resistant than that used in the theoretical design. As the water cuts into the canal bank, portions of it above the water line are left suspended, and they fall into the canal when the weight of the suspended portion exceeds the vertical shearing strength of the bank material. The portions that fall into the canal either dissolve and become suspended material (silt) floating downstream or remain approximately at the place where they fell, as chunks of eroded material, impeding the free flow of water. Lining of canals to above the high-water line is the remedy for a condition of this kind. Lining to prevent seepage may be accomplished with inexpensive materials such as silt itself, whereas lining to prevent erosion must be of a more substantial material such as asphalt or concrete. The latter class of materials, which are not subject to erosion, are also relatively watertight. Hence lining with materials of this class performs two functions at the same time—prevents seepage and prevents erosion, the latter reducing sedimentation in canals.

The principal question involved is one of cost. Although reinforced concrete is almost the perfect lining, it is nearly always the most costly. Research has been conducted and is still going on, and more is required, to find other materials, including other forms of concrete, with substantially the same properties as reinforced concrete but lower in cost.

If the value of water can be approximated, it then becomes a matter of simple mathematics to determine the amount that can be economically spent on sealing a canal for any given cross section. For example, assume a 50-mile canal designed to carry 1,320 cubic feet per second with a velocity of 4.72 feet per second. Its cross-sectional area = 1,320/4.72 = 280 square feet. With side slopes of 1½:1 and a 40-foot bottom, the radius = 4.6 and the wetted perimeter = 280/4.6 = 61 feet.

With a 1-foot freeboard on each side, the total perimeter = 63 feet.

If the canal in question has an annual inflow of 200,000 acre-feet and 25 percent of that inflow can be recovered by sealing, and if the water is considered to be worth \$2 per acre-foot, the annual saving will be worth \$100,000. At 3 percent interest, over a 40-year period (assuming the life of a lining material to be 40 years), \$100,000 will retire an investment of \$2,311,479.

The canal owner can afford, therefore, to spend \$2,311,479 to seal the 50-mile canal, or \$46,230 a mile, or \$8.76 per foot of canal.

The allowable cost per square yard for lining will then be equal to $(8.76 \times 9)/63 = \$1.25$.

In other words, a canal lining that will be good for 40 years and will not exceed \$1.25 per square yard installed must be found.

This example, of course, may not give sufficient weight to the extreme need for additional water now developing generally throughout the West. A close study of the economic factors influencing the value of water may result in the assignment of higher values, thereby justifying a greater expenditure for lining.

When the cost of overcoming sedimentation by eliminating silt at its source is prohibitive or impractical, the inflow of silt into canals may be reduced by the construction and operation of desilting basins. These may be of two types: (*a*) gravity, and (*b*) mechanical. Gravity-type desilting basins are usually found at the beginning or head of irrigation canals. They consist of a stilling basin where the flow of water is reduced to the point that the bulk of silt suspended in the water is dropped. Through wasteways to the adjacent river, the accumulated silt is flushed out periodically. An example of the gravity type of desilting basin is to be found at the head of the Interstate Canal on the North Platte project in eastern Wyoming.

Mechanical desilting basins operate by allowing water to pass into chambers where rotating scrapers feed the settled silt into a central collecting trench, from which it flows through sludge-collecting pipes into the river. An example of the mechanical type of desilting basin is that for the All-American Canal at Imperial Dam near Yuma, Arizona. This is a comparatively new development, and further experience and experimentation should develop still more efficient desilting apparatus.

The second problem, the reduction of the cost of removal of silt from the canals, is of major interest when measures to reduce or eliminate the silt carried by the irrigation water are too costly or impracticable.

Reduction of the cost of maintenance can be accomplished through lining, through other improvements in canal design, and through improved designs of cleaning machines. As previously mentioned, lining is a problem of economics—to determine how much money can be spent for that purpose. If the cost of the lining is within the economic limit, it should be installed. If not, it will be more economical to continue periodic cleaning of a canal in an unlined condition, and to devote attention to improving the efficiency of cleaning machines.

Other improvements in design of irrigation systems should reduce the cost of maintenance arising from sedimentation. In lined canals along steep hillsides, where the accumulation of silt results from storm-water inflows from adjacent lands, cleaning can be eliminated or reduced by building overpasses or covers over the canal to prevent silt-laden storm water from entering, or by the construction of underdrain culverts. Storm-water culverts under canals must be designed to have sufficient velocity to keep silt moving to preclude the necessity for cleaning the culverts. In modern design, where a canal crosses a draw or storm-water drain, inverted pipe siphons are generally provided.

Cleaning of irrigation canals is currently performed in several different ways: (*a*) by hand, (*b*) by draglines, and (*c*) by other machines. Cleaning by hand, with shovels or other hand tools, is usually expensive but is sometimes employed where labor is plentiful and the condition of the canal, owing to narrow or unstable banks, does not permit use of a heavy machine.

The standard dragline does a fairly efficient mechanical job of removing silt from the canals and restoring the original canal section.

The machine is costly to operate, and its speed of operation for this purpose is not great. Its chief advantage is in cleaning the larger canals, which the more mobile blades and dredges cannot handle. Tractors are sometimes used on small canals, a bulldozer blade or a special blade attachment adapted to the particular type of canal being used. Another type of machine in use for many years in irrigation ditches is the so-called Ruth dredger, a system of small buckets fastened to an endless belt operating at right angles to the canal; it removes dirt from the canal and deposits it on the outside of the canal bank, the machine moving on wheels or tracks along the canal bank. Although some improvements have been made in cleaning machines in past years, there still remains a challenge for the development of a canal-cleaning machine that will be cheap in operation and rapid in accomplishment.

COST OF CLEANING CANALS

The cost of removing silt from irrigation-distribution systems varies with every project and with every canal and lateral within a project. Seemingly identical operations vary from project to project because of different machines, the skill and resourcefulness of operators, and the silt conditions encountered. Each section of canal or lateral to be cleaned presents its individual problem of access: right-of-way in which to work; right-of-way to dispose of the excavated material; type, quantity, and moisture content of the silt deposit; type and density of weeds; height of banks; and strength and condition of lining—all of which affect the rate at which personnel can work and, consequently, the overall cost.

Some examples of the cost of cleaning silt are found in Table 1, which shows recent costs for representative federal reclamation projects. Average costs of silt removal on a system basis varied from \$19 per mile of canal on the Yuma project, which received desilted water, to \$187 per mile on the North Platte project. As the total mileage is used as an index and the actual mileage cleaned in any one year would be somewhat less, actual costs per mile are higher. The ratio of silt removal to total operation and maintenance costs is shown in Table 2. These ratios varied from 3.8 percent on the Tule Lake Division of the Klamath project to 29.1 percent on the Main Division of the Klamath project.

These data again illustrate the economics of siltation of canals. By careful study of cost data the prevention of silt at its source can

TABLE 1

COST OF REMOVING SILT FROM CANALS AND LATERALS

District or Project	Miles of Canals and Laterals	1945		1946		1947		1948	
		Total cost	Av. cost per mile	Total cost	Av. cost per mile	Total cost	Av. cost per mile	Total cost	Av. cost per mile
Klamath, Oregon-California									
Main Division	360	$16,759	$ 47	$21,430	$ 60	$17,212	$ 48	$18,472	$ 51
Tule Lake Division	200	15,177	76	17,669	88	11,207	56	4,426	22
North Platte, Nebraska-Wyoming									
Farmers Irrigation District	70	11,771	168	11,371	162	12,171	174	13,085	187
Gering and Ft. Laramie I.D.	310	13,022	42	11,419	37	13,029	42	16,780	54
Goshen I.D.	385	15,209	40	16,176	42	11,507	30	17,361	45
Northport I.D.	30	3,800	127	3,200	107	3,600	120	4,000	133
Pathfinder I.D.	805	23,909	30	34,351	43	28,266	35	24,123	30
Orland, California	140	2,975	21	3,941	28	5,776	41	8,647	62
Yuma, Arizona-California									
Reservation Division	215	5,723	27	4,415	21	4,142	19	6,337	29
Valley Division	75	14,494	193 [1]	21,992	293 [1]	26,726	356 [1]	17,136	23

[1] Postwar rehabilitation program.

Note: Actual cost per mile for most districts would be greater than the figures shown, because the actual mileage cleaned in any one year is less than the total mileage.

be justified to a computed degree. For example, from Table 1 it can be seen that costs were high after the close of the war, while deferred maintenance was being overcome. But even in 1948 the cost of silt removal averaged about $40 a mile, or 15 percent of all operation and maintenance costs. For the 120,000 miles of irrigation canals and laterals in the western states, the annual bill for cleaning silt would be $4,800,000. With allowance for districts receiving water from silt-free streams, the annual bill would still be over $3,500,000.

Removal of silt is not limited to unlined ditches. On the Central Valley project in California, the concrete-lined Contra Costa Canal was cleaned with a water-propelled scraper at the cost of $6.50 per mile in 1946. If the canal is cleaned twice annually by this method, the annual cost per mile is $13. This does not include any proration of the original cost or depreciation of the equipment, which was developed on the project and constructed of pipe framing, lumber, and some scrap materials that were available. The scraper could not be used in unlined canals or in lined canals where the silt deposits were extremely heavy. The smaller concrete-lined East Contra Costa

TABLE 2

COST OF REMOVING SILT AND TOTAL COST OF OPERATION AND MAINTENANCE

District or Project	1945			1946			1947			1948		
	Cost of silt removal	Total cost O. & M.	% Silt of total	Cost of silt removal	Total cost O. & M.	% Silt of total	Cost of silt removal	Total cost O. & M.	% Silt of total	Cost of silt removal	Total cost O. & M.	% Silt of total
Klamath, Oregon-California												
Main Division	$16,759	$ 57,495	29.1	$21,430	$ 89,718	23.9	$17,212	$102,987	16.7	$18,472	$129,194	14.3
Tule Lake Division	15,177	71,321	21.3	17,669	108,744	16.2	11,207	118,661	9.4	4,426	124,741	3.5
North Platte, Nebraska-Wyoming												
Farmers Irrigation District	11,771	80,706	14.6	11,371	93,500	12.2	12,171	90,828	13.4	13,085	97,651	13.4
Gering and Ft. Laramie I.D.	13,022	75,753	17.2	11,419	78,755	14.5	13,029	106,985	12.2	16,780	155,919	10.8
Goshen I.D.	15,209	81,740	18.6	16,176	74,274	21.8	11,507	85,538	13.5	17,361	93,517	18.6
Northport I.D.	3,800	15,791	24.1	3,200	14,842	21.6	3,600	28,632	12.6	4,000	22,212	18.0
Pathfinder I.D.	23,909	132,288	18.1	34,351	175,275	19.6	28,266	184,868	15.3	24,123	174,150	13.9
Orland, California	2,975	48,640	6.1	3,941	53,780	7.3	5,776	60,304	9.6	8,647	75,507	11.5
Yuma, Arizona-California												
Reservation Division	5,723	39,137	14.6	4,415	50,396	8.8	4,142	62,595	6.6	6,337	69,966	9.1
Valley Division	14,494	163,434	8.9	21,992	288,413	7.6	26,726	346,726	7.7	17,136	355,215	4.8

Canal was cleaned by more conventional methods in 1946 at a cost of approximately $37 per mile.

The Turlock Irrigation District, in California, has a total of 125 miles of lined canals in which occurs a moderate amount of silting. The presence of the silt, however, as in all lined canals, encourages the growth of algae and certain types of mosses and leads to decreases in the canals' carrying capacities that are greater than the reductions in cross-sectional areas would indicate. For this reason, the district removes the silt deposits and other debris at the close of the irrigation season each year. Equipment developed in the district, consisting of a truck equipped with a boom and scraper arrangement that minimizes the hand work required is used, and the average cost of cleaning all sizes of canals is $50.

On the Shoshone project in northwestern Wyoming, 3.8 miles of the Deaver Canal (194 second-feet) were cleaned with a dragline in 1945 at a cost of about $1,020 per mile. This figure includes allowance for depreciation on the equipment. Small laterals were cleaned on the Shoshone project in 1947 with a one-way Chatten ditcher pulled with a tractor, at a cost of about $50 per mile. Excavation in cleaning the laterals with this machine averaged about 1 cubic yard of material for every 15 linear feet.

The Bucyrus-Ruth excavator, or Ruth dredger, is used on many irrigation projects for cleaning laterals and small unlined canals. On the Belle Fourche project in South Dakota, 29 miles of laterals were cleaned in 1946 with a Ruth dredger, at a cost of $85 per mile. Also in 1946, approximately 8 miles of laterals on the Milk River project in northern Montana were cleaned at a cost of about $147 per mile. Between 50 and 75 miles of laterals on the Lower Yellowstone project in eastern Montana were cleaned each year during the years 1932 to 1946, inclusive, at an average cost of $75 per mile. Depending on the size of the lateral and the variation of silt deposit, weeds, willows, tules, and other vegetative growth, the cost of cleaning laterals with this type of excavator varies from $50 to $150 per mile of lateral.

Before the desilting works were installed for the Imperial Irrigation District at Imperial Dam, the cost to remove silt from its canal system averaged over $700,000 annually. This was approximately $250 per mile for the lengths of canals and laterals cleaned each year in the entire system. The cost of silt removal from the distribution systems since construction of Imperial Dam and desilting works has been much less than the previous cost, and the deposit in the All-American Canal itself has been negligible. Suspended material carried in the Yuma Canal before Hoover and Imperial dams were built was 30 times the amount of the material that is carried now by water passed through the desilting works.

The construction of Imperial Dam and the desilting works cost a total of about $10,000,000, of which $4,526,000 was charged to the desilting works alone. Amortizing this amount in 40 years, without interest, develops an annual cost of $113,150. The annual operation and maintenance costs of the desilting works, in the four years 1945 through 1948, averaged $69,000. Assuming this figure as an average, the total annual cost of the Imperial Dam desilting works would be less than $200,000, which represents a saving of at least $500,000 per year resulting from this construction.

RESEARCH NEEDED

Sedimentation in canals is an unwelcome expense on the water users served by irrigation projects of the West. To reduce this burden as much as possible, further research is needed into both the sources and causes of silt and the methods of removal where elimination at the source is not practical. These are fields for both the geologist and the several branches of engineering.

More information is needed about the relation between the condition of the watershed and the amount of silt carried by streams. Although the desert areas of the Southwest are often considered the major sources of silt, more attention must be given to the burned and overgrazed areas in all parts of western United States. The U. S. Forest Service has done considerable work in determining the effect of forest fires and overgrazing on soil erosion and stream siltation. The correlation of those data with the percentage of silt in irrigation water on its arrival at the project is still to be developed. If the direct relationship between denuding of forested areas and the cost of silt removal from irrigation canals can be shown, the farmers on irrigation projects will be more active supporters of forest-conservation programs. It should be possible to develop by research, for example, the actual cost of a forest fire or overgrazing to irrigation systems dependent on the watershed affected, and to show the actual increase in cost of removal of silt arising from such causes. Information of this kind would also support a program for reforestation of burned-over areas and should contribute materially to securing congressional and state appropriations for that purpose.

The design of desilting basins should be improved to provide for removal at a minimum of cost of silt suspended in irrigation water. The trapping of silt in gravity basins is essentially a process of shifting the silt burden from one irrigation system to another, as the sluicing of the silt back into the river merely permits the river to carry the same load to the areas farther downstream. A method is needed for deposition or treatment of silt so that it will no longer be available for water transportation. Refinement in design of mechanical desilting basins to reduce both the initial cost and the cost of operation and maintenance to the lowest possible extent is important. As with the gravity basins, the problem of disposal of the accumulated silt is one for further study. Merely sluicing it back into the river from whence it came is no solution, even though there may be no additional irrigation downstream. Silt bars in the river greatly affect its regimen and can cause unexpected and expensive difficulties with water tables and drainage of adjacent agricultural lands, even though the irrigation water has been clarified to a reasonable degree. Too often the engineer of today passes this problem on to the engineer of tomorrow, and tomorrow always comes.

Development of low-cost canal linings is an active possibility. The Bureau of Reclamation presently has a program for that purpose and has made some progress in exploring its potentialities. There still remains, however, opportunity for considerable original research with as yet unknown materials that may be adapted to canal linings. Such materials might include those of plastic origin; sheet metals, such as aluminum; and chemicals, such as asphalt and bentonite, which, when mixed with earth, develop an impervious seal.

Improvement of canal-cleaning machines is a fertile field. Whereas improved designs have been made in nearly all forms of agricultural machinery and in construction of irrigation systems, there has been little improvement in machines used for cleaning canals. The invention and manufacture of a rapid, efficient, and cheap cleaning machine would bring considerable fame and fortune to its developers, inasmuch as there are in the West approximately 128,000 miles of irrigation canals and laterals on both federal and private projects which are still growing and which must be periodically restored in order to maintain irrigation service to the 21,000,000 acres now being cultivated.

Aside from the actual work of making surveys, conducting engineering research, and improving maintenance procedures, there is another task that should be performed in the interest of increasing the available knowledge of sedimentation of canals. The engineering literature is replete with reports, articles, and books on sedimentation and erosion, some of which are listed in the attached bibliography. The files of government agencies such as the Bureau of Reclamation and the Soil Conservation Service contain much unpublished material on the subject. A book should be prepared to bring all information together from the Kennedy formulas of India to the latest data available on sedimentation in the canals of the Unted States. Economic formulas to develop the value of watershed treatment, lining of canals, and improvement of cleaning machinery are urgently needed.

In conclusion, the problems of sedimentation in irrigation canals are not insurmountable. The causes and effects are generally known. How to keep silt out of irrigation water and how to reduce the cost of removal of sedimentation are problems for geologists and engineers. Once their reports are available, the problem becomes a matter of money, personnel, and time, balanced in total against the cost of letting Nature take her course unchallenged. Much remains to be done to lower the cost of removing silt by improving the design of desilting basins, by developing low-cost canal lining, and by improving cleaning machinery. With the cost of silt removal frequently exceeding 15 percent of the operation and maintenance budget, or over 3.5 million dollars annually, it takes a sufficient sum out of the pockets of farmers each year to justify further research and expenditure of public and private funds to continue and carry forward this specialized field of sedimentation.

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Chapter 22

EFFECTS OF SOIL CONSERVATION

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CAUSES AND RATES OF SEDIMENT PRODUCTION

This chapter is concerned with erosion and sediment production on watersheds: their lands, drainways, and stream systems; with the rates and sources of sediment production; with the effects of erosion and sedimentation on man's use of land and water resources; and with the potentialities for soil and water conservation.

Geologically normal rates of erosion and sedimentation materially affect man's enterprises in some watersheds, mainly in arid regions. By far the largest number of sediment problems stem, however, from man's disturbance of the prehistoric geologic norm (Lowdermilk, 1934). Clean-cutting and burning of forest and brush lands, overgrazing of grasslands, and the cultivation of crop lands have greatly reduced the primeval vegetal protection of the land surface against the erosional attack of raindrops, surface runoff, and wind action (Bennett, 1939; Glenn, 1911). The resulting erosion of the soil mantle over much of the earth has been accelerated far beyond the rate of soil formation, with which it was formerly in balance on most sloping lands. The associated formation of countless gullies and valley trenches has greatly increased channel density (length of channels per unit area). The erosion of these new channels directly contributes large quantities of sediment to stream loads (McLaughlin, 1947; Thornthwaite *et al.*, 1942). They also act as flumes through which erosional debris can be delivered more rapidly from much larger areas of the land surface to geologically developed stream systems. This, alone, has changed the regimen of many streams, setting up a chain of events that materially affects the utilization of such natural resources as stream flow, reservoir sites, and flood-plain lands. In some watersheds, alteration of natural drainageways by deepening and straightening, by construction of dams, diversions, jetties, and levees, and by regulation of stream flow has further aggravated channel erosion and sedimentation.

Several lines of evidence indicate that man-induced erosion has increased the sediment load of streams in the humid areas of the United States in the order of 25 to 100 times, and of most streams in the arid

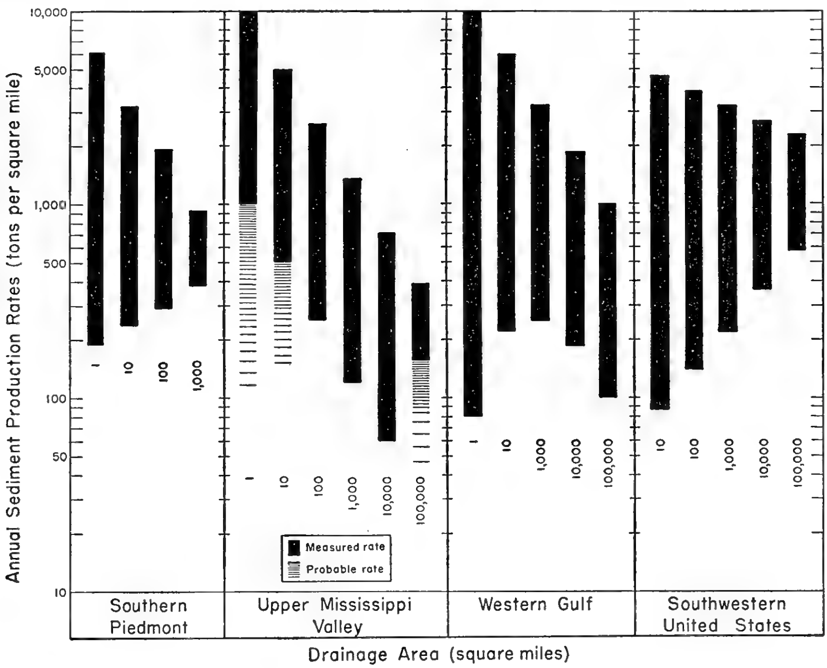

FIG. 1. Annual sediment production rates.

and semi-arid areas by probably at least 2 to 4 times (Brown, 1948).

Present rates of sediment production have been determined for several hundred watersheds in the United States by sampling the suspended load of streams and by measuring sediment accumulation in reservoirs (Brown, 1945b; Brown and Thorp, 1947; Brune, 1948; Eakin, 1939; Faris, 1933; Fippin, 1945; Fortier and Blaney, 1928; Howard, 1947; Stevens, 1936). The rates have been found to vary over a wide range for watersheds ranging in size from a few acres to drainage areas of more than 100,000 square miles. In general, the smaller the watershed, the greater is the range, as shown in Fig. 1. This could be anticipated because smaller watersheds have greater contrasts in the factors that influence sediment production, such as average slopes, drainage

TABLE 1

REPRESENTATIVE RATES OF SEDIMENT PRODUCTION FROM LARGER DRAINAGE AREAS IN THE UNITED STATES[1]

State	Stream	Nearest Location	Drainage Area	Period of Record	Average Annual Sediment Production
			sq. mi.	yr.	tons per sq. mi.
1. Maryland	Gunpowder Falls	Baltimore	299.4	29	890
2. North Carolina	West Fork, Deep River	High Point	33	6.58	584
3. North Carolina	Yadkin River	Salisbury	3,930	7.8	595
4. South Carolina	Enoree River	Greenville	64.4	4.5	278
5. South Carolina	South Tiger River	Woodruff	174	4.25	727
6. Georgia	Ocmulgee River	Jackson	1,414	24.3	532
7. West Virginia	Tygart River	Grafton	1,182	7.0	51
8. Ohio	Wills Creek	Senecaville	115	8.3	1,026
9. Ohio	Clear Fork, Mohican River	Perrysville	198	6.25	292
10. Illinois	Sangamon River	Decatur	902	24.2	341
11. Wisconsin	Coon Creek	Stoddard	119	4.0	616
12. Iowa	Raccoon River	Van Meter	3,410	5.53	1,359
13. Iowa	Des Moines River	Boone	5,490	5.53	512
14. Iowa	Mississippi River	Keokuk	119,000	33	229
15. South Dakota	White River	Oacoma	10,200	8.0	1,765
16. Iowa	Soldier River	Pisgah	417	7.0	10,384
17. Nebraska	Missouri River	Omaha	322,800	9.0	479
18. Wyoming	North Platte River	Guernsey	5,500	20.0	285
19. Colorado	South Platte River	Henderson	4,740	5.0	224
20. Nebraska	Platte River	Ashland	83,800	9.0	162
21. Nebraska	Republican River	Bloomington	21,037	5.0	768
22. Kansas	Big Blue River	Randolph	9,099	5.0	1,208
23. Missouri	Gasconade River	Jerome	2,861	5.0	368
24. Missouri	Osage River	Osceola	8,220	5.0	768
25. Colorado	Arkansas River	Pueblo	4,730	5.0	229
26. Colorado	Huerfano River	Undercliffe	1,710	6.0	796
27. Colorado	Apishapa River	Fowler	1,130	6.0	3,127
28. Colorado	Purgatoire River	Highland Dam	3,320	6.0	1,855
29. Colorado	Arkansas River	Las Animas	14,500	6.0	288
30. Oklahoma	Spavinaw Creek	Spavinaw	400	11.0	884
31. Texas	Red River	Denison	32,840	6.3	633
32. Louisiana	Sabine River	Logansport	4,858	13.2	253
33. Texas	Neches River	Rockland	3,539	17.1	146
34. Texas	Elm Fork, Trinity River	Dallas	1,174	10.5	1,300
35. Texas	Trinity River	Romayor	17,200	11.1	425
36. Texas	Double Mt. Fork, Brazos River	Aspermont	1,510	9.2	2,690
37. Texas	Navasota River	Easterly	949	5.7	441
38. Texas	Brazos River	Richmond	34,810	23.3	1,092
39. Texas	Llano River	Llano	4,000	5.2	54
40. Texas	Colorado River	San Saba	18,800	17.1	255
41. Texas	Guadalupe River	Spring Branch	1,432	5.7	135
42. Texas	Nueces River	Three Rivers	15,600	20.0	51
43. New Mexico	Pecos River	Ft. Sumner	3,749	6.9	1,510
44. New Mexico	Rio Puerco	Rio Puerco	5,160	5. +	2,430
45. New Mexico	Rio Grande	Elephant Butte	26,312	32.4	680
46. Utah	Green River	Green River	40,600	12	592
47. Utah	Colorado River	Cisco	24,100	12	749
48. Utah	San Juan River	Bluff	23,900	12	1,861
49. Arizona	Colorado River	Grand Canyon	137,800	16	1,453
50. Arizona	Gila River	Coolidge Dam	12,900	18.3	389
51. Arizona	Salt River	Roosevelt Dam	5,760	30	1,170
52. Utah	Sevier River	Marysvale	1,878	28	253
53. Nevada	Willow Creek	Elko	126	15	202
54. Idaho	Boise River	Boise	2,170	32.6	146
55. Idaho	Payette River	Emmet	2,540	12	172
56. California	San Leandro Creek	Oakland	30.3	17	2,470
57. California	Little Stoney Creek	Colusa County	98.9	35.2	231
58. California	Mokelumne River	Stockton	383	14	206
59. California	Merced River	Merced	1,022	19.6	226
60. California	Santa Inez River	Santa Barbara	215.4	24.6	1,935
61. California	Santa Anita Creek	Arcadia	10.8	10.2	6,054
62. California	Sweetwater River	San Diego	181	59	1,433
63. California	Cottonwood Creek	San Diego	112	25.7	3,903

[1] From suspended-load measurements and reservoir-sedimentation surveys, not corrected for bed load, trap efficiency, channel aggradation, mean runoff, etc.

density, soil and rock types, and particularly land use (Brown, 1946). The larger the watershed in any given hydrologic region, the more these differences are ironed out. In certain regions a tendency toward decrease in the rate of sediment production per unit area with increasing size of area has been noted. Apparently this trend is caused by the progressive downstream deposition of sediment on flood plains and elsewhere throughout the watershed. However, in several major drainage basins, incoming tributaries cause a progressive downstream increase. For example, the sediment load per unit area of the Missouri increases downstream to Sioux City, and of the Mississippi downstream to the mouth of the Missouri (Brune, 1948). Selected rates of sediment production are given in Table 1.

SOURCES OF SEDIMENT

Practically all stream-borne sediment comes from one or more of the following sources:

Sheet erosion of the land surface. Sheet erosion is the more or less uniform removal of soil or soil material from the land surface by the forces of raindrop impact and surface runoff, or wind action. Most sheet erosion by water involves the formation of rills or minor gullies. If these are not too deep (more than about 6 inches) to be obliterated by cultivation or to be crossed by wheeled vehicles, they are considered part of the phenomena of sheet erosion (Fig. 2).

Gullying. Gullies are channels, generally more than 6 inches deep, eroded by concentrated runoff in soil, alluvium, or decomposed and unconsolidated rock. It seems desirable to confine the term gully to channels cut where no well-defined or continuous channels formerly existed. Thus defined, the arroyos or valley trenches in alluvium-filled western tributary valleys could be considered gullies, but enlargement of formerly existing channels of a watershed drainage system would be classed as stream-channel erosion (Fig. 3).

Stream-channel erosion. This is defined as erosion of the banks and scouring of the beds of geologically developed perennial or intermittent streams. In so far as this form of erosion is a source of sediment production, a net enlargement of the channel is implied. Many streams are eroding their banks, often causing severe losses of agricultural bottom land, but the losses are balanced by deposition within the channel, so that there is no net increase in the sediment load reaching a point downstream (Fig. 4).

Mass movements. These include landslides, slumps, avalanches, soil creep, etc. (Fig. 5).

FIG. 2. Sheet erosion on 12 percent slope cultivated in straight rows and planted to corn, near Bethany, Missouri.

FIG. 3. Enormous gullies more than 50 feet deep and less than 100 years old cut in rich agricultural land 8 miles west of Lumpkin, Stewart County, Georgia.

FIG. 4. Stream-bank erosion along Wynooche River 5 miles northwest of Montesano, Grays Harbor County, Washington.

FIG. 5. Mass movement of soil by landslip in pasture 8 miles north of Wolf, Ohio.

Flood erosion. Flood erosion results from the scouring action of flood-water overflow on the surface of flood plains and alluvial fans. As in stream-channel erosion, this may or may not result in a net sediment production (Fig. 6).

Construction erosion. This term is used to include all soil and earth movement produced directly by construction of roads, railroads, power

FIG. 6. Flood erosion as a result of flood-water scouring in cultivated field on Ohio River flood plain after flood of January 1937.

lines, dams, building projects, etc. It includes also the erosion resulting from lack of proper maintenance of these properties, including the effects of scraping earth roads and erosion of unprotected cuts and fills (Fig. 7).

Mining and industrial wastes. This includes all forms of waste dumped into streams or left in positions favorable to erosion (Adams, 1944) (Fig. 8).

Some forms of natural geologic erosion do not fall strictly within a single one of these classes. For example, the recession of cuesta faces, or the "breaks" of the plains, are a combination of sheet erosion and minor gullying, often accompanied by slumping and other mass movements. However, a type of erosion that does not fall within a single

Fig. 7. Road erosion in watershed of Burlington Reservoir, Alamance County, North Carolina.

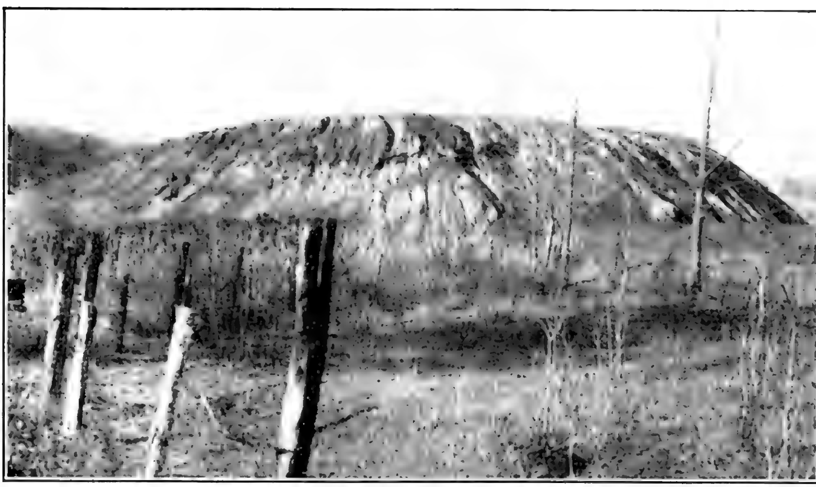

Fig. 8. Mine waste dump of Docena Mine adjacent to Bayview Reservoir near Birmingham, Jefferson County, Alabama.

class is rarely an important source of the total sediment production from any sizable watershed.

The preceding classification makes no distinction between geologically normal and accelerated erosion. Sheet erosion and gullying have always occurred on sparsely vegetated land in semi-arid regions. The rate has varied almost directly with the density of vegetal cover, and to a more limited extent with the type of cover (U. S. Forest Service, 1936). When the density and type of cover change, whether with varying precipitation or because of overgrazing and burning of the cover, the rate of sheet erosion will naturally change (U. S. Forest Service and Soil Conservation Service, 1940). The concept of "accelerated" erosion, however, implies a change due to man-induced depletion of the cover and other uses of the land. In forested or densely vegetated areas, geologically normal erosion of the land slopes occurred primarily by soil creep and subsequent removal of the creep material by stream-bank erosion (Lowdermilk, 1934).

Sheet, gully, and stream-channel erosion are by far the most important sources of the sediment load of most streams. Sheet erosion generally produces a major part of the sediment load of streams over broad areas that are predominantly agricultural and have more than 20 inches of precipitation. Sediment that causes particular problems such as channel aggradation may come, however, primarily from gullying or other sources. In most forest and range country, and in areas having less than 20 inches of precipitation, gullying and stream-channel erosion generally furnish the greater part of the total stream load. In small watersheds any of the other sources may be the most important. Specific data on sources of sediment in certain watersheds have been previously published by the writer (Brown, 1944).

THE SOIL-EROSION PROBLEM

According to the U. S. Census of 1945, continental United States contains approximately 1,905 million acres of land. Of this total, 148 million acres, or nearly 8 percent, has been classified as mountains, mesas, and badlands.

Of the remaining 1,757 million acres, which is used or is potentially useful for cropping, grazing, or timber production, about 282 million acres, or nearly 15 percent of the total, has been severely eroded since the white man first occupied the land. On the average, more than 75 percent of the original topsoil has been removed by surface runoff and wind action. Much of the land is severely gullied. Approximately 100,000,000 acres of this class of land, or about 5 percent of the total land area of the country, has been essentially ruined for further cultivation.

About 775 million additional acres, or nearly 41 percent of the total area of the country, has been moderately eroded; 25 to 75 percent of the original surface soil has been lost; occasional to frequent gullies are present; and in places moderate wind erosion is evident.

The remaining 700 million acres, or a little less than 37 percent of the total, has suffered either no erosion or only slight erosion, with removal of less than 25 percent of the original topsoil. In this class is most of the flood-plain and delta lands, swamps, and the nearly flat plains and prairies.

The U. S. Soil Conservation Service estimates that the productive capacity of about 110 million acres will be permanently damaged, and about 500,000 acres annually will be essentially ruined for further cultivation unless this land is placed under a sound conservation farming system within the next 10 to 15 years. On another 110 to 120 million acres, soil erosion is proceeding at a less rapid but still serious rate. To prevent serious or irreparable damage to these lands, they should be safeguarded by conservation treatment within the next 15 to 30 years.

Most agricultural specialists agree that, with present farming practices, seed varieties, and available fertilizer, about 2½ acres of crop land per person is needed to provide a United States "normal" standard-of-living diet (based on an average family income of $2,000). An additional one-half acre is needed to provide other essentials such as clothing and shelter. At 3 acres per person, the estimated 1949 population of 150 million would thus require 450 million acres of crop land. The Soil Conservation Service estimates the maximum potential crop land in the United States that can be developed and permanently maintained under existing economic conditions at 466 million acres (that is, land that can be safely used indefinitely under rotation systems of farming and with adequate conservation practices, irrigation, drainage, flood protection, etc.).

The United States population for 1975 has been variously forecast at 162 to 185 million persons (U. S. Congress, 1948). Assuming a median value of 174 million, an increase of 24 million, an additional 72 million acres should be available by that date to maintain without further soil deterioration the present normal standard of living at existing rates of crop production per acre. There is a difference of only 22 million acres, however, between the 444 million now needed and the estimated 466 million acres of potential crop land. Thus, even with due allowance for probable increased yields per acre resulting from extensive agricultural research, it seems apparent, as contended by Osborne (1948) and Vogt (1948), that the nation faces a choice of (1) control of its population increase, (2) a declining standard of living within a generation or two, or (3) immediate action toward conservation of its productive soil resources. Despite the large expenditures currently being made for reclamation of arid land and, to a lesser extent, drainage of wet lands, the most serious task confronting the nation is the maintenance of its existing crop land, particularly prevention of the estimated loss of 500,000 acres annually due to gullying and other forms of erosion that make further productive use of the land virtually impossible.

SEDIMENT PROBLEMS

Sediment problems can be conveniently grouped into four categories (see Fig. 9): (1) suspended-sediment concentration in water; (2) sedimentation (including erosion and degradation) in natural stream channels, improved river channels and harbors, floodways, ditches, and canals; (3) sedimentation (including scour) on land, improvements, and habitats; (4) sedimentation in reservoirs.

In each category specific problems can be related either (1) to the need for control of one or more of the seven sources of sediment production previously described or (2) to the need for control of sediment at the site of the problem (for example, proper design of irrigation-diversion works to exclude bed load at the head of main canals). A detailed treatment of every type of problem in terms of its causes and remedies would obviously be beyond the scope of this chapter (U. S. Bureau of Reclamation, 1948b). Other chapters deal specifically with several of these problems. The treatment here will be confined to the relation of sediment control on the watershed to the alleviation of the several types of problems. The urgent need for remedial action is emphasized by the magnitude of sediment damages, which have been estimated by the writer to be approximately $175,000,000 annually.

Suspended-Sediment Concentration in Water

Sediment suspended in flowing or impounded water may have a harmful effect on (1) water supply, (2) recreation, (3) commercial fishing, (4) flood control, and (5) power generation.

Suspended sediment must be removed from surface water before it is potable or suitable for most industrial uses. Garin and Forster (1940)

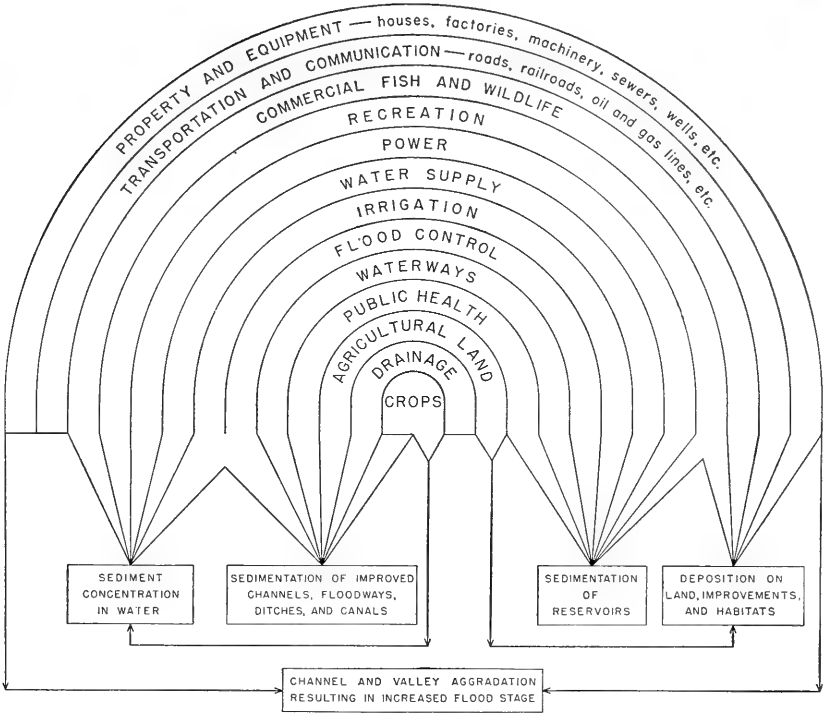

Fig. 9. Effects of sedimentation.

found that on an average, in the piedmont section of North Carolina, an increase of turbidity from 100 to 1,000 parts per million required a 70 percent increase in the quantity of alum used to flocculate the sediment. Higher turbidity also necessitated more frequent cleaning of settling basins and increased certain other costs. Most of the sediment that is filtered from surface water is fine-textured, ranging from silt to colloids, and in most streams it comes mainly from widely disseminated sheet erosion (Garin and Gabbard, 1941). Except where water-intake characteristics or plant facilities could be improved, reduction in the costs of water treatment can be accomplished only by widespread control of soil erosion on the watershed.

Fine suspended sediment seriously impairs the value of streams and lakes for recreational use. It reduces the population of game fish and lessens the desirability of water for swimming (Brown, 1945a). It also causes heavy losses of commercial-fish and shellfish yield from both inland and tidal waters (U. S. Congress, 1946). With few exceptions, these losses may also be attributed to widespread soil erosion on tributary watersheds.

On a few western streams and in the headwater tributaries of some eastern streams, the quantity of sediment transported by flood flows is sufficient to cause a higher stage and greater area of inundation than if the flows were free of sediment. Maximum daily concentrations as high as 13.8 percent by weight in the Colorado River at Grand Canyon, Arizona (Howard, 1947), and 21 percent in the Rio Grande at San Marcial, New Mexico, have been recorded. Samples taken on the Rio Puerco, a major tributary of the Rio Grande, have contained more than 60 percent of sediment by weight, and samples from small streams in Iowa have ranged as high as 27.6 percent of sediment. In the small, steep mountain watersheds above Los Angeles, California, flood flows caught in debris basins (Eaton, 1936) contained 85 percent of solids by volume (after settlement) and only 15 percent of free water (above the amount required to saturate the deposit). These examples are extreme conditions for both large and small streams. Most of the large streams of the country seldom transport more than 1 to 3 percent by weight of sediment at any time. Many eastern streams never approach this value. As a concentration of 10 percent by weight causes a volume increase of only about 4 percent in the flow, it is obvious that only high concentrations will significantly increase the flood stage and resulting area of inundation.

Coarse sediment passing through the penstocks of run-of-the-river power plants has been known to abrade the turbine blades and necessitate frequent replacement. This material is almost entirely bed-load material, the immediate source of which is stream-bed scour.

Sedimentation in Channels, Harbors, Ditches, and Canals

Sedimentation (and scour) of channels affect (1) flood damages and flood control by increasing or decreasing the size of stream channels and floodways; (2) navigation of (*a*) inland rivers and (*b*) harbors; (3) drainage through (*a*) open canals and (*b*) the level of the water table under agricultural land; and (4) irrigation water-distribution systems.

If a stream channel is progressively becoming smaller because of aggradation, the area of inundation for a given flood discharge will progressively increase. Conversely, if the channel is enlarging by erosion, the area of inundation will decrease. Almost without exception, flood-damage-frequency studies have been based on an assumed constant channel capacity. Actually, in many watersheds, particularly on the headwater tributaries, channels and first-bottom floodways are being progressively reduced in cross-sectional area by aggradation; consequently future flood flows of the same volume and duration will cause a higher stage and greater area of inundation.

The Middle Rio Grande Valley is a classic example in the United States of channel and floodway aggradation (Happ, 1948; Rittenhouse, 1944). Throughout the 150-mile length of this valley the river is generally confined by levees except for a stretch about 17 miles long above the original head of Elephant Butte Reservoir. Cross-section surveys showed that the average annual sediment accumulation in the floodway during the 5 years from 1936 to 1941 was 3,312 acre-feet. This is equivalent to an average aggradation of about 1 foot in 12 years.

In the Kickapoo River watershed, Wisconsin, the channel and first bottom have aggraded at an average rate of approximately 1 foot in 20 years since the beginning of cultivation, about 1850 (Happ, 1944). From Ontario to the mouth of the river, flood heights increased an average of 2.5 feet for the same discharge up to 1940. Continuation of this trend until 1960 would cause an estimated increase of approximately 40 percent in damage to seven urban areas built on low terraces adjacent to the present flood plain. Similar conditions have been found in some streams in almost every section of the United States (Adams, 1944; Brune, 1942; Gilbert, 1917; Happ, 1945; Happ *et al.,* 1940; U. S. Congress, 1942; U. S. Bureau of Reclamation, 1948b).

In some places channel aggradation is a local phenomenon resulting from backfilling of sediment behind obstructions in the channel, such as fallen trees. The stream would be capable of passing through the sediment load delivered to it if these obstructions were periodically removed. In many watersheds, however, the present rate of coarse-sediment production exceeds the stream's capacity to deliver this part of its load to its mouth, and general aggradation is resulting (Happ *et al.,* 1940). The only permanent solution in such cases is to reduce the supply of coarse sediment or to increase the stream's transportation capacity. Reservoirs for holding back bed sediment and sills or barriers for stabilizing channel scour and stream-bank and gully erosion are generally the most immediately applicable control measures.

In some watersheds where the load is largely fine and carried in suspension, the flood-plain surface is aggrading while the channel bed remains constant or is being degraded. This condition is, of course, decreasing the stage and area of inundation for a given flood discharge.

Reservoirs upset the regimen of alluvial-bed rivers, causing aggradation of channels upstream and degradation downstream (Hathaway, 1948). On the Colorado River at Needles, California (U. S. Bureau of

Reclamation, 1948a), for example, an aggraded channel condition can be traced to bed scour upstream induced by construction of Hoover Dam, which desilted the river flow. This illustrates the fact that the cause of a channel problem must be understood in order to plan proper corrective measures. In this case, erosion control on the watershed area below Hoover Dam would have no significant effect on the problem.

The basic causes of problems incident to the maintenance of navigable channels on inland rivers are not always clear. Usually they appear to be due to natural river meandering and shifting of the bed with rising and falling stage (Fisk, 1947; Friedkin, 1945). Engineers familiar with the navigation problems of the Mississippi, Missouri, Ohio, and other large rivers are predominantly of the opinion that increased sediment production from the watershed is not a primary factor in channel maintenance. They believe generally that minimization of maintenance costs depends on securing the most favorable alignment, grade, bank protection, and control of discharge.

On the other hand, the maintenance of most harbor channels is caused by deposition that takes place when the inflowing river can no longer transport its load after reaching tidewater (Gottschalk, 1945). In some places tidal currents and wave action bring littoral sediment into harbors, but available data indicate that this is a minor cause of harbor-maintenance costs compared with the deposition of stream-borne sediment generally derived from disseminated sources on tributary watersheds.

Silting of open-drainage canals is an aggravated problem in many parts of the country. Runoff coming directly from watershed lands often carries more coarse sediment than the canals, with their lower grades, can transport. Canals draining swamps and marshes, on the other hand, ordinarily carry desilted water and have no sediment problem. Vegetative growth in canals increases their roughness, thus decreasing their sediment-carrying capacity. It has been found that, sometimes, the sediment load is "excessive" only because of this growth. Its removal enables the flow to erode the channel to its original dimensions. More generally, however, control of soil erosion on the drainage area is the only applicable remedy.

Irrigation canals are subject to much the same problems as drainage channels. Since water is diverted into them, however, their sediment content can often be controlled by properly designed diversion works or desilting devices (Parshall, 1947). Because irrigation canals usually do not follow the natural drainage lines of a watershed, they must cross many minor waterways. Unless they are adequately protected at such points or the minor watersheds are protected, storm flow in these waterways may breach the canal and deposit sediment for some distance along it.

DEPOSITION ON LAND, IMPROVEMENTS, AND HABITATS

Sedimentation (with associated scouring and swamping) on flood plains and other areas of overflow damages (1) agricultural land; (2) property, facilities, transportation, and communication; and (3) recreation and wildlife habitats.

The damaging effects of infertile sediment deposits, flood scouring of topsoil, and swamping due to drainage derangement on valley agricultural lands are so widely distributed that nearly every part of the country has such problems (Brown, 1945c; Happ, 1945; Happ *et al.*, 1940; U. S. Congress, 1942, 1946; U. S. Bureau of Reclamation, 1948b). These are, like soil erosion, cumulative damages to land. Whereas flood-water damage can be correlated with stage, duration, frequency, and season of flood flows, and its recurrence interval can be computed by available hydrologic techniques, sediment damage is progressive and can be evaluated only with respect to the average rate of development.

Studies made by the Soil Conservation Service (Happ *et al.*, 1940) have shown that conditions in most valleys, especially in the headwater reaches, were essentially stable prior to deforestation and cultivation. Changes due to stream meandering and overbank flow took place slowly. In areas with more than 20 inches of rainfall, old, slowly developed, dark topsoils now serve as key horizons from which subsequent changes during the period of accelerated erosion can be measured. In hundreds of valleys these old topsoils have been buried by rapidly accumulated and, generally, less fertile "modern" sediment. The validity of this dating has been frequently confirmed by fence posts, mine wastes, bricks, and other artifacts buried in the "modern" sediment but never below the dark topsoils; by releveling old profiles; and by studies of the contrasting physical characteristics and watershed sources of modern sediment and old soils. Valley agricultural damage per acre of overflowed land is generally greater in headwater valleys and becomes progressively less downstream. In some watersheds, however, there is evidence that the locus of greatest damage is moving progressively downstream.

The causes of damage to flood-plain agricultural land are as varied as the problems and their locales. In many places local channel obstructions are forcing flood flows out of bank, causing scour and deposition. More often, however, damages can be attributed to greatly increased loads of coarse sediment and greater frequency of overflow.

Accelerated sedimentation on flood plains has been traced to all the sources previously described.

Measures that reduce the frequency of inundation will reduce future depositional and erosional damages, except bank erosion which, without bank protection, may possibly be more rapid at bank-full stage than at overflow. Levees and related flood-control works will not restore soil already impaired or lost. Direct land and channel improvements will be required to reclaim lands that already have been damaged. Reduction of the sediment supply by watershed treatment or reservoirs, however, will tend to cause channel deepening and, hence, increased discharge capacity, lowered water tables, and reduction in the average acreage damaged.

Damages to other than agricultural land result from sediment deposition on streets, in houses, machinery, sewer lines, and wells, from which it must be removed before the facility can be again used. Much of the loss reported as due to flood damage, however, has, in fact, been due to sediment (Brown, 1945c). Prevention of inundation, of course, will eliminate this damage, but it can be lessened to some extent by any methods that tend to reduce the sediment load of the stream regardless of their effect on flood stage.

SEDIMENTATION IN RESERVOIRS

Most impounding reservoirs are constructed for power, irrigation, flood control, water supply, recreation, navigation, or multiple purposes. Sedimentation damages a reservoir when it reduces the storage capacity to the point where the reservoir cannot supply the full services for which it was designed (Brown, 1944; Edgecombe, 1934). Sometimes deposition on beaches, in boating areas, etc., may cause damage even though the capacity loss is negligible.

Regulating storage is required in connection with most hydroelectric installations in order to maintain a high rate of primary power production. Any loss of reservoir capacity for such storage, therefore, causes some damage, as it decreases the minimum constant flow that can be maintained through the power turbines. When periods of spillway overflow are followed by periods of low runoff during which the power pool level is drawn down, the direct loss from silting can be measured by the kilowatt-hours of electrical energy that could have been produced by previously wasted water equal in volume to the sediment deposited in the zone of drawdown. Continuity of the rate of power generation makes the difference between primary and secondary power. The greater the fluctuation in power output from hydroelectric plants, the more stand-by sources of power, such as steam plants, must be operated. To the extent that this is necessitated by reduced storage capacity, the silting damage may be measured by the added cost of operating stand-by plants. Damages may thus be said to start with the beginning of storage and sedimentation.

Sedimentation damage to irrigation reservoirs is likewise measured primarily in terms of the value of water wasted over the spillway that could have been retained and used. Some of the largest reservoirs in the Southwest (Elephant Butte, New Mexico; San Carlos, Arizona; and Roosevelt, Arizona) were built with sufficient capacity to impound two or more times the average annual stream flow. Water wastage over the spillway may be expected, therefore, only in years of exceptional flood discharge; and water deficiency attributable to this loss during exceptional droughts may have an average recurrence interval as long as 25 years or more. With cumulative storage loss from sedimentation, however, the recurrence interval of water deficiency progressively decreases. Hence crop losses will become more frequent. Theoretically, and often practically, damage begins with the initiation of storage. Furthermore, sedimentation in irrigation reservoirs tends to increase the evaporation loss by increasing the surface area of water exposed for any given volume of water in storage. Sediment deposits in the upper end of reservoirs generally become covered by water-consuming vegetation, and the resulting heavy evapo-transpiration, especially in the more arid states, may represent a critical loss of available water. (For reports on recent surveys of irrigation reservoirs, see Seavy, 1948a, b, 1949.)

If a flood-control reservoir is designed to prevent overflow below it from a flood flow of 100-year average recurrence interval, a calculable damage results if its detention capacity is reduced by sedimentation to the point where it can control fully only a 75-year flood flow. In this case also sedimentation damage begins as soon as the reservoir is completed. Flood control is often provided, however, by gate-controlled detention storage above the pool level maintained for power production, water supply, or irrigation (U. S. War Department, 1943). In such multiple-purpose reservoirs, loss of flood-water-detention capacity ordinarily occurs slowly because of the relatively infrequent and short periods of impoundment. Flood control may not be seriously affected until the storage capacity at lower levels is greatly depleted. Some reservoirs, on the other hand, are constructed solely for flood control, with large outlets at the base of the dam. The outlets, gated or ungated, are generally designed so that flood-water detention will not begin until the flow downstream is near bank-full stage. Much of the water passes through such reservoirs at normal stream-discharge velocities; hence much of the sediment load may pass through and out of the basin.

Sufficient capacity must be maintained in domestic and industrial water-supply reservoirs to assure continuity of supply during periods of prolonged drought and to meet normal increases in water demand over a reasonable number of years. If such reservoirs are built with capacities far in excess of reasonable requirements, the additional cost represents in effect prepaid insurance against loss by silting. If the capacity is just about equal to the reasonable requirements, any reduction by silting represents a direct damage which involves both an accumulating loss of service value and a future replacement cost (Brown *et al.,* 1947).

In recreation reservoirs, sediment creates conditions unfavorable to fish life; accumulates on sandy beaches, thereby making them less desirable for swimming; impedes boating; causes swamping in the upper end of the lake and on the shores, thereby decreasing esthetic values and often property values, and in some sections of the country increasing health hazards from malaria.

Navigation reservoirs are damaged both by shoaling of ship channels, which necessitates frequent costly dredging operations, and by loss of storage capacity required for regulating low-water flows.

Various methods have been used to reduce the rate of reservoir sedimentation (Brown, 1944). The most lasting solution of the problem is reduction of the rate of sediment production from the contributing drainage area, provided that the reservoir is an efficient sediment trap and that sedimentation has not already progressed to the point where the reservoir would be useless before effective measures could be carried out on the watershed (Brown, 1946; Marshall and Brown, 1939). The sources of sediment must always be determined before an effective watershed-treatment program can be planned.

POTENTIALITIES FOR EROSION AND SEDIMENT CONTROL

Effective methods for reducing current rates of erosion have been developed and demonstrated (Bennett, 1939). Musgrave (1947) has shown that the principal causal factors of sheet erosion are: (1) rainfall, (2) slope, (3) soil, and (4) vegetal cover. By correlating a large mass of experimental data, he has developed a first approximation of the relative effects of the principal causal factors. For rainfall, the data indicate that

$$E \propto P_{30}{}^{1.75}$$

where E = rate of erosion in tons per acre of dry soil.

P_{30} = maximum 30-minute rainfall of 2-year frequency

For degree of slope,

$$E \propto S^{1.35}$$

where S = slope in feet per hundred. For length of slope,

$$E \propto L^{0.35}$$

where L = length of slope in feet.

By equating measured erosion rates for 19 different soils on which extensive data are available to a common 1.25-inch, 30-minute rainfall on a 10 percent slope 72 feet long with minimum vegetal cover, the inherent relative soil erodibility was found to vary from 0.03 to 0.96 inch per year. In other words, because of characteristic textural

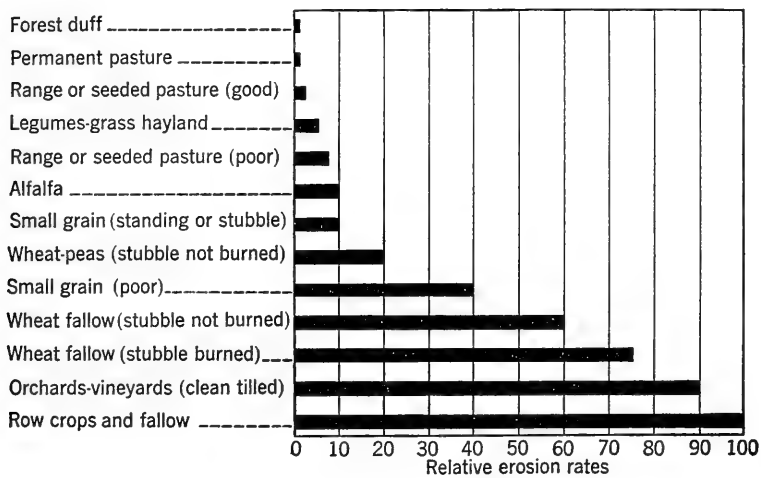

Fig. 10. Relative erosion rates under different vegetal covers in Pacific Northwest.

and structural differences of soils, an extreme variation of 33-fold in their erosion potential may be expected.

By far the greatest relative difference in rate of erosion was found to result, however, from the character and density of vegetal cover. If the same soil, slope, and rainfall are assumed, the rate of erosion on land used for continuous row crops (such as uncontoured cotton, corn, or tobacco) was found to be more than 100 times as great as on land used for hay, pasture, woodland, and forest. Figure 10 shows relative erosion values for different vegetal covers in the Pacific Northwest.

These research data give a basis for estimating the potential reduction in sheet erosion that might be achieved by modification of the causal factors. Although rainfall intensity and frequency cannot in themselves be changed, analysis of their monthly expectancy in any area gives a basis for planning maximum protection of the soil surface by cover crops, mulches, etc., in those months when the erosion potential from rainfall is greatest. The effects of length and degree of slope indicate the relative need for measures such as terraces, diversion ditches, strip crops, and benching to reduce the effective slope and break it into shorter lengths. Inherent differences in soil erodibility suggest adjustment of land use to afford greater vegetal protection of more erodible soils and more use of less erodible soils for row crops. It indicates also possibilities for reducing the inherent erodibility by changing the soil structure through tillage practices and by plowing under cover crops, mulches, and manure. Lastly, differences in effects of vegetal cover emphasize the need for rotation systems of farming, use of cover crops, and conversion of some row-crop land to permanent cover.

Experiment station data have shown (Brown, 1948) that a good 3- or 4-year rotation will reduce sheet-erosion loss to 14 to 45 percent of that occurring under one-crop system of cultivation. Contour farming, strip cropping, and terracing, under various soils, slopes, and rainfall, effect reductions ranging from 10 to more than 90 percent, averaging generally about 50 to 75 percent (Stallings, 1945a, b, c).

These experimental results have led conservationists to the conclusion that sheet erosion on agricultural land can be reduced 50 to 75 percent or more while agricultural production is sustained and improved by using every acre in accordance with its capabilities and treating every acre in accordance with its needs.

Other types of erosion may require special forms of treatment. Stabilization of major gullies, valley trenches, or stream banks, for example, may be accomplished in some places by planting of trees and vines; or, if particularly unstable, they may require small dams, revetments, jetties, or other control structures. It is physically possible in areas of more than 20 inches of rainfall to stabilize completely most gullies and virtually eliminate them as a source of sediment. The less erosion can be controlled by vegetation, the more costly the control becomes, and the more likely that it must be accomplished through some federal program such as that contemplated in the Flood Control Act of 1936 (U. S. Congress, 1936). In areas of less than 20 inches of rainfall, more reliance must be placed on structural measures such as revetments, check dams and debris basins. Economic rather than physical considerations, therefore, primarily govern the amount of reduction in sediment production that can be achieved in many watersheds, particularly those in the more arid sections of the country.

The effects of changes in land use and treatment on sediment production from watersheds have been determined in a few representative cases by repeated reservoir-sedimentation surveys.

In the Sangamon River watershed above Decatur, Illinois, more than 90 percent of the sediment is coming from sheet erosion. The rate of sediment production averaged 20 percent higher during the 10 years from 1936 to 1946 than during the preceding 14.2 years as a result of the greater use of land for intertilled row crops from 41 to 60 percent of the total watershed area. The writer and collaborators (1947) have estimated that, if farmers would adopt the recommended rotations, use contour farming, strip cropping, terracing, and other practices where needed in accordance with the capabilities of the land, the rate of sediment production from the area would be reduced by 62 percent from its rate in 1946 without reducing the level of net farm income.

By reforestation and gully control on 83 percent of an 890-acre area of rolling and badly eroded land above the municipal reservoir at Newnan, Georgia, the rate of sedimentation was reduced 62 percent during the period 1937–1945, as compared with the earlier period 1925–1937 (Brune, 1947). The reduction is progressively increasing as the watershed-treatment work becomes more fully effective.

On the 62-square-mile watershed of the municipal reservoir at High Point, North Carolina, soil-conservation measures applied on about 35 percent of the total acreage caused a reduction of 24 percent of the rate of sedimentation for the period 1934–1938, as compared with the earlier period 1928–1934 (Brune, 1947). Still other records have been cited by the writer (1944), and more data are now being obtained.

From the evidence now available, it is concluded that in the principal agricultural areas of the United States present rates of soil erosion could be reduced 50 to 75 percent or more by proper land use and treatment without decreasing the net agricultural income from the land (Brown, 1948). Rates of sediment production, as measured at a given point in a stream system, could be reduced even more by watershed-treatment measures that provide for control of channel erosion and selective deposition of erosional debris at many locations within the watershed. The limitation in controlling sediment production in the semi-arid to arid, non-agricultural regions of the United States is more economic than physical in that it depends primarily on structural control works, accompanied by rigid regulation of land for grazing. These controls can be obtained, in general, only at public expense. The high value of maintaining water-storage capacity in many western watersheds indicates, however, that the cost of reducing sediment production by some 50 percent, on an average, through watershed-treatment measures, may be justified.

RESEARCH AND PLANNING NEEDS

In few fields is such a wide variety of research and planning needed as in the conservation of the soil and water resources of the nation. Needed studies fall within the scope of soil science (particularly soil physics and soil chemistry), agronomy, ecology, biology, forestry, hydrology, geology (particularly geomorphology, sedimentation, and ground water), engineering (particularly hydraulic, structural, and agricultural), economics, and law.

Soil- and water-conservation research can be grouped functionally under the following headings:

Studies of basic forces and resistances. These include, for example, studies of the forces involved in raindrop impact; the fluid dynamics of thin overland flows of water; the mechanics of sediment entrainment, transportation, and deposition in open-channel flow; aerodynamic forces causing soil movement; and the resistances afforded by the character of the soil, degree, length and aspect of slope, and various types of vegetal cover.

Studies of the areal distribution and frequency of occurrence of forces and resistances. This research involves analysis of the geographic distribution in terms of amounts, intensities, and duration of precipitation, wind action, runoff, sediment transportation, soil erodibility, vegetal cover, and watershed characteristics such as drainage density and relief.

Development, testing, and improvement of measures and practices for the control of water erosion and moisture conservation on the land surface.

Development of methods for controlling water and sediment movement and conveyance in channels, conduits, etc.

Development of methods for water conservation and utilization in the soil and underground storage.

Development of measures and practices for wind-erosion control.

Studies of conservation economics affecting the operation and income of farms and other private land holdings, of drainage enterprises, of irrigation enterprises, and of public interests in flood and sediment control.

Studies of the legal requirements and methods of organization for carrying out programs of soil and water conservation.

Most of the physical requirements for controlling soil erosion on individual farms and ranches are being developed by several thousand soil conservationists who have brought into being a new field of research, planning, and action founded on several of the older sciences. Farm- and ranch-conservation planning and technical assistance to landowners and operators in the application of sound land-use readjustments and conservation measures, such as terracing, strip cropping, contour farming, rotations, farm waterways, and farm ponds, are within the general field of practicing soil conservationists.

In the more complex problems of planning adequate water disposal, flood and sediment control, and related farm drainage and irrigation on watersheds, the specialized experience of hydrologists, hydraulic engineers, soil scientists, and geologists is required. Sediment control, perhaps the most difficult of the conservation problems, requires the services of: (1) *hydraulic engineers* who are familiar with modern developments in the fields of hydrodynamics and fluid mechanics, with particular reference to the effect of entrainment, transportation, and deposition of sediment on open-channel behavior; (2) *geologists* who understand: (*a*) the concepts of geomorphic development of landscapes and the interpretation of land forms and drainage patterns in terms of their causal factors; (*b*) the geological aspects of sedimentation, particularly those phases involving the statistical analysis of sediment characteristics; (3) *soil scientists* who can aid in relating the characteristics of soil texture, structure, and depth that affect erosion to rates of sediment production on the watershed; and (4) *hydrologists* who can aid in the correlation of hydrologic characteristics of watersheds with rates of sediment production. The planning and design of control measures on the watershed also calls for the services of vegetative specialists, on the one hand, and the structural engineer, on the other. Experience to date has shown that most sediment problems can be solved most effectively and economically by the collective efforts of a group of specialists who have an opportunity to study and plan jointly corrective measures to meet the needs of each individual watershed.

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CHAPTER 23

THE PROBLEM OF GULLYING IN WESTERN VALLEYS *

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To distinguish between gullying and other types of erosion, the term gully is generally applied to any erosion channel so deep that it cannot be crossed by a wheeled vehicle or eliminated by plowing. When applied to the arid and semi-arid valleys of the West, this limitation regarding minimum size seems somewhat inconsistent, for with many gullies having dimensions measured in tens of feet in depth, hundreds of feet in width, and scores of miles in length, a definition aimed at distinguishing them from canyons or small valleys might have been more appropriate.

Generally the term arroyo has been used synonymously with gully, but by some (Thornthwaite *et al.*, 1942, p. 72) arroyos are considered the result of natural conditions of erosion in contrast to gullies, which have developed under "culturally accelerated erosion" or, in other words, land misuse. Because it is difficult or impossible to learn from the appearance of the channel the conditions under which it developed, the distinction has little significance, and in this discussion the less euphonius but more descriptive term "gully" will be used.

Gullies appear to have been a common feature of stream erosion in the recent geologic history of western valleys and possibly have always formed a part of the landscape in localities favorable to their development. Evidence of former gullies, similar in cross section and dimensions to existing ones, can usually be found wherever any extensive section of fine-textured alluvial fill is exposed. Just as at present, gullies have developed in localities underlain by soft, easily eroded materials, which offered minimum resistance to downcutting. It is difficult to determine the extent of this earlier gullying or to ascertain whether the channels were integrated into a continuous system wherein the gradients of all branches were accordant with the parent stream,

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or whether they occurred as discontinuous segments, each developed individually with no relation with its neighbor, except for being aligned along a common drainage course. Both types exist today, so it may logically be presumed that they occurred previously.

Although possibly the most destructive and certainly the most spectacular in appearance, gullies represent only one phase of water erosion. They may even be subordinate so far as silt removal from a given locality is concerned, being surpassed in this respect by rilling or by the much less prominent sheet erosion occurring on interfluviatile areas. What constitutes their critical and insidious threat is the lowering of the base level within the drainage system, which exposes to potential removal all material within the basin above this level. A long gully of narrow dimensions may represent the removal of only a few thousand acre-feet of silt, but potentially it has set the stage for removal of hundreds of thousands.

That gullying is not confined to the arid and semi-arid West is shown by its widespread evidence in other localities, but when consideration is given to the problems involved in attempting to control or ameliorate western gullies, complications of unique nature immediately become apparent. As will be shown, the area affected by gullying is of tremendous extent, but the value of the land on a per-acre basis is extremely low, so low that treatment of only a minor nature can be justified on the basis of land improvement alone. Despite the low value, however, the lands are the major support of the western livestock industry, and practically every acre is utilized for grazing to the full limit of its forage production. Authority for such use is established on the basis of either direct ownership or legally recognized leases or permits. The vegetative cover that supports the livestock also forms the major, if not the only, effective protection against erosion. Sparse and erratically distributed precipitation in which droughts of several years' duration alternate with flash floods of tremendous eroding power is characteristic of almost the entire area. The problem of maintaining a vegetative cover under these conditions is readily envisioned.

Further to complicate the problem, many of the remedial measures applied thus far to a limited extent in an attempt to correct erosion have been of very doubtful success, thus raising the pertinent question whether our knowledge of the meteorologic, ecologic, hydrologic, and geologic aspects of the problem is extensive enough to permit designing a practical treatment program that will have a reasonable chance of accomplishing the desired results.

As an example of western gullies, one embodying the common history and features associated with channels of this type, the San Simon gully of southwestern Arizona, might be considered typical. From its confluence with the Gila River near the town of Solomonsville, Arizona, this gully cuts southeasterly for nearly 70 miles through the heart of the lower San Simon Valley. The gully is not continuous, as one short reach of the valley floor, approximately 2 miles in length situated some 40 miles above the mouth, is uncut. It is not known if this reach has previously been dissected, but it is evident that unless remedial measures are taken the two discontinuous segments will shortly be integrated into one continuous channel. In depth, the gully, in both branches, varies from 6 to 60 feet; in width from 75 to more than 1,000 feet. Surveys made by the U. S. Soil Conservation Service * in the middle 1930's show that silt removed from the main trench is of the order of 20,000 acre-feet. Additional excavations from gullied tributaries and from sheet and badland erosion on interfluviatile belts adjacent to the bank, both traceable in the main to rejuvenation resulting from development of the master gully, probably equal or exceed this amount. Prior to the 1929 completion of Coolidge Dam, located on the Gila River some 70 miles downstream, silt disposal from the eroding area offered no particularly critical problem. Since that date it has become a very real threat to the life of the San Carlos Reservoir.

The San Simon Valley, like many others of its kind located throughout the West, contains a deep alluvial fill which originated as outwash from the surrounding mountains. Older portions of the fill, represented by both lacustrine and continental deposits, form a part of the Gila conglomerate of late Pliocene and Pleistocene age, described in the literature by Knechtel (1937). These beds, which are usually indurated to some extent, are exposed around the margins of the valley, and although extensively dissected they generally exhibit no serious recent erosion.

Distributed along the central axis of the valley and extending mountainward along the tributaries, are deposits consisting of clay, silt, and fine sand intermixed with occasional lenses and stringers of coarse sand and gravel. These are typical flood-plain deposits obviously laid down by gently flowing streams capable of carrying fine-textured sediments only, except during periodic floods, when the coarse sand and gravel were brought in. Archaeologic evidence † indicates that

* Unpublished data obtained through personal communication with earlier employees of U. S. Soil Conservation Service.

† Personal communications from Dr. Emil Haury, Department of Anthropology, University of Arizona, furnished probable dating of artifacts found in the valley.

these deposits were laid down within the past few thousand years, but that it was not a continuous process of aggradation is shown by the presence of numerous filled channels and well-defined erosional surfaces within the fill. It is evident that, at various times in the past, erosion similar in character to, and possibly as extensive as, that taking place today has occurred.

At the time of white settlement of the adjacent Safford Valley in the late 1870's, the San Simon Valley is said to have presented a picture of pristine beauty.* Its floor was flat and unbroken. Reportedly large areas in the central portion were covered with grass thick enough and tall enough to be harvested for hay. San Simon Creek, dignified by some of the earlier explorers with the appellation "river," was perennial throughout most of its length and meandered across the valley floor in a shallow channel, lined for most of its length with trees and willows. Stockmen naturally recognized this as an ideal grazing setup, and during the 1880's, 50,000 head of cattle are said to have populated the valley.

The present gully is reported to have started in the early 1880's when farmers constructed a small drainage ditch to carry flood waters of San Simon Creek across farm lands adjacent to the Gila River. It reportedly did not reach serious proportions, however, until 1905. By then, grazing combined with the critical ten-year drought, extending from 1895 through 1904, had eliminated the protective grass covering on the valley floor, leaving it "ripe" for gullying. The record wet winter of 1904–1905 with a winter seasonal index of wetness of 246 (the highest on record) provided the runoff necessary to accomplish this. Just how far the cutting advanced in this one season is not known, but, to judge by the meager progress measured in the past few years, probably the major portion of the present channel was excavated during this short period.

Today's picture of the valley, from both the conservation and the range-use viewpoint, is one of devastation. Except in the short uncut reach, the former grassy tracts now appear as barren flats, some completely devoid of vegetation, others supporting only an occasional stunted bush or clump of grass. In places along each side of the channel, belts up to several hundred feet in width and several miles in length have been stripped of topsoil to depths of 3 feet or more. Some of these remain essentially flat, and others have deteriorated into miniature badlands with a relief of 2 to 6 feet. The stream has long since lost any semblance of permanency, and the ephemeral flows are

* Information obtained from interviews with several early settlers.

marked by sudden peaks and rapid recession, the magnitude of flow depending on the intensity and duration of the accompanying rain since there is little vegetation to either impede or decrease the runoff by inducing percolation. The headcuts and gully banks remain vertical as a result of sapping and undercutting by these periodic flows. Although most of the major tributaries of the San Simon are still uncut, side drainage pouring over the vertical banks, particularly opposite the unprotected barren tracts, has incised literally hundreds of short deep channels and subterranean passages, leaving the terrain next to the bank cut into narrow fingers and isolated blocks of soil. Under these conditions the potential silt contribution to the Gila River from the San Simon Valley is enormous, being limited only by the amount of water available for transportation, since the sediments themselves offer little if any resistance to removal. Typical views of the present condition of the San Simon gully are shown in Fig. 1.

With suitable modification for differences in length and dimensions of the gully, character of the valley fill, history of gully development, and other details, the picture of the San Simon could be transposed to a myriad of other valleys located throughout the West. The control of these gullies is essentially the major erosion problem of the West.

DISTRIBUTION OF GULLIES

Gullies similar to the San Simon, some greatly exceeding it in size and destructiveness, are common throughout the Southwest. In New Mexico the gullied valleys of the Rio Grande, including the Rio Puerco, the Jemez, and the Salado, have been described in such detail and are so well known as to be familiar to those having only a casual acquaintance with the erosion problems of the area, but scores of others of almost equally impressive dimensions also occur in the basin (Bryan and Post, 1937; National Resources Committee, 1938). In the Gila River drainage, the valleys of the Santa Cruz, the San Pedro, the Mangus, and the San Simon represent only the larger of numerous gullied tributary valleys distributed from near the headwaters of the river almost to the mouth.

Although possibly not so prevalent as in southern latitudes, gullies nonetheless occur in large numbers in the headwater areas of the Missouri and its tributaries. Particularly is this true of the Bighorn and Powder rivers in Wyoming. One familiar with these streams will immediately call to mind such striking examples as Five-Mile, Muddy, E-K, and Badwater creeks in the Wind River Basin; Fifteen-Mile, Cottonwood, and Dry creeks in the Bighorn Basin; and Mispah and Pumpkin creeks and Little Powder River in the Powder River Basin. These are but a few among many. Milk River in the north has a similar, though perhaps smaller, quota, the Willow Creek gully (some 25 miles in length and averaging approximately 20 feet in depth and 100 feet in width) being a prime example. Tributaries of the North Platte River, draining from Casper Mountain in central Wyoming, exhibit a network of gullies seldom duplicated in other localities.

Parts of the Columbia River Basin are likewise checked with the telltale gully scars. The greatest development has already occurred in the semi-arid wastes of eastern Oregon and Washington, but many valleys in Idaho and northern Nevada show evidence of the same action.

Probably the most advanced and critical development of gullying is found in the Colorado River Basin. Examination by the Inter-Mountain Forest and Range Experiment Station (Bailey, 1937) reveals that, of the 115 major tributaries of the Colorado and Green rivers above Lees Ferry, 111 have been trenched by gullies. The combined total length of these channels and their associated tributaries is thousands of miles, and the material removed in these excavations probably aggregates hundreds of thousands of acre-feet. Stevens (1936, p. 1254) and Stabler (1936, p. 281) have focused attention on the paradoxical position of the Colorado Plateau in regard to silt and water contribution to the Colorado River. The Plateau area, comprising about 65,000 square miles, or 45 percent of the drainage basin of the Colorado above the Grand Canyon, contributes less than 10 percent of the water but more than 75 percent of the silt entering the stream. Practically every valley within the area is gullied.

Tributaries of the Colorado entering below the Grand Canyon, including the Bill Williams River, Meadow Valley Wash, Virgin River, and Kanab Creek together with most of their tributaries, present the same picture. Even valleys which at present make no pretense of possessing creeks or rivers (these terms are used in the optimistic sense peculiar to the West, and one must be on the spot at the proper instant even to glimpse the flow of water) have not escaped being gullied, as evidenced by the spectacular trenches found in the lower reaches of the Sacramento and Bouse valleys located in some of the driest parts of western Arizona.

An examination of numerous tributaries of some of the large Great Basin streams, such as Bear River in Wyoming and Idaho, Sevier River in Utah, and the Humboldt, Truckee, and Walker rivers in Nevada, reveal the same pattern of gullying. Even smaller streams that drain some of the driest parts of the Basin, as, for example, Thousand Springs Creek in northeastern Nevada and Snake Creek in western Utah, have, in parts of their drainage area, developed gully systems that rival those existing in more humid areas. The fact that both cutting and the concurrent deposition in these remote areas affect only low-value lands accounts for the lack of attention thus far accorded the areas.

PRACTICAL ASPECTS OF THE GULLY PROBLEM

The above review of the widespread prevalence of gullying is presented to emphasize that the phenomenon is not limited to any one locality or governed by any set of conditions relative to topography, geology, soils, or climate; it is obvious that, throughout this vast area, wide and contrasting variations in these features must occur. Mountain valleys, with slopes ranging up to one or two hundred feet per mile, exhibit the same gully characteristics as do others with slopes of only 10 to 15 feet per mile. And, although as noted, gullies are somewhat more prevalent in areas such as the Colorado Plateau and portions of the High Plains and Rocky Mountain provinces, where the valley fills are derived from surrounding friable sandstones and shales, they also occur in almost equal numbers in southern Arizona and other localities where the alluvium originates from mountains composed of igneous, volcanic, or highly indurated sedimentary and metamorphic rocks. Dimensions and shapes of the valleys likewise appear to have little influence, for the small fan-shaped basin with limited drainage area commonly may be as deeply and extensively incised as its larger elongated counterpart.

Although trenching and the destruction of land within the affected valleys constitute a serious phase of the problem, because the attack is aimed directly at the more productive portions of the range, this aspect is possibly of less importance than the disposition of the removed silt. The few figures, such as the previously mentioned survey of the San Simon and a similar estimate by Bryan and Post (1937, p. 86), which shows that nearly 400,000 acre-feet have been removed from the main and tributary channels of the Rio Puerco, are significant only as indicators. Were the surveys extended to cover all the hundreds of other major gullies, aggregating thousands of miles in length, an even more disturbing picture would be revealed. Except where silt from these valleys is deposited without damage on low-value lands within interior basins, it enters and becomes the serious sedimentation problem of the major streams. Thus the problem has a dual aspect: de-

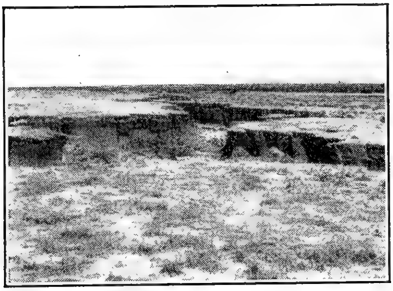

FIG. 1(*a*). View upstream near head of the San Simon gully, Arizona.

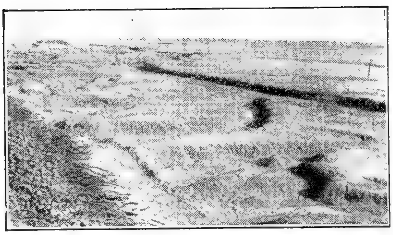

FIG. 1(*b*). Badlands developing adjacent to San Simon gully, Arizona. Main channel not shown. Note brush and rock spreader in left foreground.

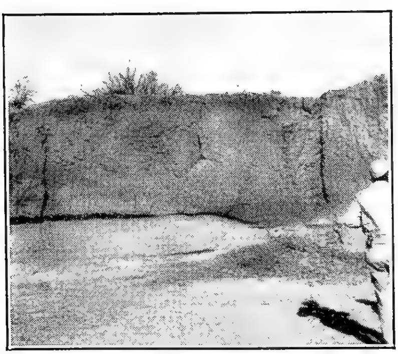

FIG. 1(*c*). Erosional unconformity exposed in walls of San Simon gully, Arizona. Top layer is brown silt, bottom layer is pinkish gray clay.

FIG. 2(*a*). Headcut on a tributary of Rio Puerco, near Cabezon, New Mexico. Height 40 feet.

FIG. 2(*b*). Headcut of Willow Creek gully, tributary of Milk River near Glasgow, Montana. Height 25 feet. Hay meadow directly above.

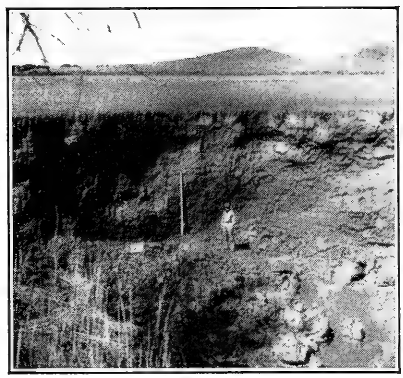

FIG. 2(*c*). Recently gullied channel in Centennial Wash near Salome, Arizona. Height about 12 feet.

struction of land, on the one hand, and constantly mounting difficulties relating to silt disposal, on the other.

MECHANICS OF GULLY CUTTING

Gullies follow a simple pattern of development which is characteristic in all localities. Almost invariably they are marked by vertical or nearly vertical headcuts and banks which give them a typical rectangular cross section. Once established, the headcuts advance, and the channels widen by sapping and undercutting the banks. Abrasion by flowing water, either at the falls or above, is a relatively minor cause of enlargement. The depth of cutting and the gradient of the downstream channel vary widely, apparently dependent on a function of the flow, the character of the eroding sediments, and the slope of the valley floor. Depths ranging from a few inches to 60 feet have been observed.

Advancing in this manner, gullies may cut for an indefinite distance without any disturbance of the surface, either laterally or upstream, beyond the confines of the channel (Fig. 1*a*). Also, because cutting generally takes place at depths below the reach of plant roots, the presence of even dense vegetation above headcuts has little if any influence on the rate of advancement (Fig. 2*b*).

The upstream progress of headcuts occurs at highly variable rates which depend on the volume and duration of flow and on the character of the eroding sediment. A headcut can remain inactive for a period of years, then under proper conditions of flow it may progress hundreds or even thousands of feet within a few hours or days. Table 1 shows the measured progress of a number of headcuts during the past few years. The relatively insignificant progress made by the gullies during the past few years (which in most of the localities shown have been abnormally dry) strongly suggests that most of our long gully systems have been developed mainly during the few years that produced extraordinary floods. Unfortunately no records on growth are available for these years, but how else can one account for the San Simon moving only a few hundred feet in 6 years when it has cut nearly 70 miles in the 44 years since its beginning in 1905? The condition is one that should be considered in making an estimate, on the basis of known records, of long-term silt carried by any particular stream, for, unless the period of record contains its quota of these wet seasons, the estimate can be highly erroneous.

TABLE 1

MEASURED PROGRESS OF GULLY ADVANCEMENT

Gully Designation	River Basin	Date of Initial Survey	Date of Check Survey	Progress	Approx. Total Length of Gully	Approx. Date Gully Started
				feet	miles	
San Simon Creek, southwestern Arizona	Gila River	Feb. 1944	Feb. 1946	10	65	1905
		Feb. 1946	Oct. 1948	50		
Centennial Wash near Salome, Arizona	Gila River	Feb. 1945	Mar. 1947	75	10	1920?
		Mar. 1947	Dec. 1948	600		
Deadmans Wash near Shiprock, New Mexico	San Juan River	Jan. 1944	Oct. 1948	160	2	1910
Hogback Wash near Shiprock, New Mexico	Chaco River	1936	Feb. 1946	200	1	1920
Unnamed wash near Shiprock, New Mexico	Mancos River	1936	Feb. 1946	150	10	Unknown
		Feb. 1946	Oct. 1948	0		

CAUSES OF GULLYING

As gully cutting represents but one aspect of erosion, consideration of its cause involves an inquiry into the broad phases of the erosion problem. Specifically, erosion may be assumed to occur in a given locality when the resistance of the surface to erosion is less than the erosive power of the eroding agent. Thus, in gully formation, which is clearly the result of water action, the erosion may logically be attributed to a condition that either lowered the resistance of the surface in a given locality or increased the size or the velocity of the stream. A combination of the two would make the action doubly effective.

As the fine-textured alluvium that floors practically all the western gullied valleys has little if any inherent cohesion, the greatest resistance to erosion is afforded by the protective vegetative cover. Depletion or destruction of this cover in any manner sets the stage for incipient erosion under normal conditions of flow, and, likewise, flows of extraordinary magnitude might also be expected to accomplish the same action under normal condition of cover.

Recognition of the critical nature of the erosion problem, particularly since the early 1930's, has stimulated much study of both its cause and methods for curing or ameliorating it. As could be expected, the studies have evoked controversies on both points which, unfortunately, are no nearer settlement today than when first advanced. Doubtless these differences reflect the extreme complexity of the problem and the tenuous and uncertain nature of the evidence available for its interpretation.

In general two theories have been advanced as the cause of the recent excessive erosion of the West. Advocates of the first ascribe gullying exclusively to land use, or misuse, the chief form of which is overgrazing, but establishment of roads and trails and other activities which locally destroy the protective vegetative cover are also included. From this conception has developed the term "accelerated erosion," now so widely used in the literature on conservation. Advocates of the second theory consider the present cycle merely another in the sequence of similar events that happened previously, each ascribable to slow changes in climate wherein aggradation occurred in wet and degradation in dry periods. Adherents of this theory hold generally that overgrazing merely acted as a trip to set off in advance events which were ultimately bound to happen. It is to be noted that there is no disagreement among advocates of either school regarding the importance of vegetation in controlling erosion, nor does either side deny that vegetation has deteriorated. Opinions are split only on the cause of the deterioration.

A third suggestion, that increase in stream gradient resulting from regional or differential uplift has been the cause of recent increased erosion, has been considered by some as completely untenable (Bryan and Post, 1937, p. 78) and, by others, has been accorded only minor consideration chiefly because of the difficulty of obtaining substantiating evidence. Another possibility, that irrigation diversion from the many western streams has had an influence on initiating the gully cycle, has not, in the writer's opinion, been given the study it merits. It appears entirely logical to conclude that interference with the regimen of a stream, particularly where diversions have affected the natural protective bank vegetation, might well lead to changes in the parent channel that would be reflected in the tributaries.

The arguments for and against the two principal theories are voluminous, and there is no need for their review except to point out a few of the salient features of each.

Land Misuse

It would appear that the occurrence of widespread gullying shortly after the white man deployed his herds across the West was no coincidence. According to Bryan (1925), Gregory (1917, p. 130), Thornthwaite, *et al.* (1942, pp. 102–104), and the testimony of many living witnesses, most of the important gullies of the Southwest began in the 1880's. Generally those in northern latitudes were cut at a somewhat later date, but most were cut before 1900. By this time, the livestock population equaled or was approaching that of the present, as indicated by Fig. 3, and advocates of the overgrazing theory conclude that range use had already been sufficient to disrupt the delicate balance between aggradation and degradation previously established in these valleys.

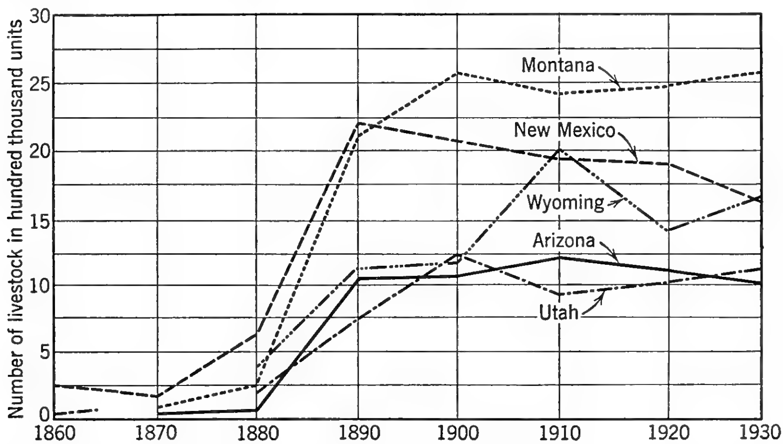

FIG. 3. Livestock population in western states, 1860–1930. Data from U. S. Census reports. Livestock numbers have been reduced to common basis by considering 5 sheep equivalent to 1 cow or horse. Prior to 1890, animals on the farm only were reported; beginning with 1890 the figures include animals both on the range and on the farm.

It is natural to assume that the first herds concentrated on the valley floors, where the best feed existed and where water was available. This subjected these vulnerable areas to intense and perhaps destructive use before more remote portions of the range were seriously affected. This suggests, therefore, that the initial cutting was due to lowering the resistance to erosion on the valley floors rather than to changes affecting the runoff.

It is also known, however, that the Southwest at least was subject to large, if not unprecedented, floods during this same period, and practically every account of gully cutting mentions a rain or a flood of extraordinary magnitude (see particularly Thornthwaite *et al.*, 1942, pp. 102–104; Woolley, 1946, pp. 87–90). As no stream-flow records are available for the period, comparison with floods experienced since is precluded, but precipitation data at a few stations in the Southwest

TABLE 2

ANNUAL PRECIPITATION AT SELECTED STATIONS FOR THE YEARS 1881–1884, INCLUSIVE

Station	1881	1882	1883	1884	Long-Term Average
Benson, Arizona	8.60	9.64	10.57	8.69	10.12
Bowie, Arizona	15.92	17.90	13.86	25.20 [1]	12.74
Ft. Apache, Arizona	31.12 [1]	27.62	21.55	29.47	18.23
Ft. Grant, Arizona	18.96	14.82	15.48	25.67 [1]	14.38
Granite Reef Dam, Arizona	7.24	9.10	10.61	20.95 [1]	9.86
Phoenix, Arizona	8.91	6.94	7.40	12.83	7.43
Univ. of Arizona, Tucson	14.92	15.59	17.53	15.03	11.50
Prescott, Arizona	15.45	14.26	16.13	26.75	18.53
Silver City, New Mexico	30.82 [2]	19.27	20.28	.....	17.40
Deming, New Mexico	20.80	8.71	9.36	7.68	9.66
El Paso, Texas	18.17	8.27	12.92	18.29	9.05
Ft. Bayard, New Mexico	30.82 [1]	19.27	20.36	.....	15.67
Lordsburg, New Mexico	17.46	8.74	6.42	13.19	9.54
Roswell, New Mexico	19.90	9.91	17.04	28.73 [2]	14.88
Santa Fe, New Mexico	22.25 [3]	11.37	14.76	19.67	14.27
San Diego, California	5.00	9.74	8.01	27.59 [1]	10.08
Los Angeles, California	5.53	10.74	14.14	40.29 [1]	15.43
Riverside, California	3.95	5.78	5.54	25.32 [1]	11.50
San Bernardino, California	5.46	10.67	12.76	37.08 [1]	16.08

[1] Maximum of record.
[2] Second maximum of record.
[3] Fifth highest of record. Excelled in 1854, 1855, 1856, and 1865.
Data from Climatic Summary and other records, U. S. Weather Bureau.

furnish indications of extraordinary rainfall and consequent runoff. Table 2 shows the precipitation at 19 stations in the Southwest for the period 1881 to 1884, inclusive, compared with the long-term mean. Eleven of the 19 stations had the maximum rainfall of record (the records at most stations being continuous to the present time) during one of the four years.

Speculation about whether the valleys would have been cut by floods generated during this record precipitation had there been no previous grazing by imported livestock is of little value, because proof is impossible, but that serious floods and erosion did occur in certain localities prior to range depletion is shown by Woolley (1946, p. 87), who lists the occurrence of four floods in Utah by 1854, only 7 years after the arrival of the first pioneers. Two of the floods carried immense quantities of debris and mud, indicating advanced erosion even under practically virgin range conditions.

The most serious criticism of attributing recent cutting exclusively to overgrazing is that it fails completely as an explanation for earlier periods of erosion which occurred long before the area was disturbed by the white man's herds. Hack (1942), Sayles and Antevs (1941), Albritton and Bryan (1939), and Bryan (1926) have described the evidence of such previous erosion at various localities in the Southwest. The writer has found similar evidence in the San Simon Wash of Arizona previously mentioned. The numerous filled channels that can be found outlined in the banks of most existing gullies are also considered positive indications of former gully systems at least approaching the present ones in depth and extent.

Overgrazing, as a prerequisite to erosion, likewise fails to explain the occurrence of erosion in areas that have never been used. Gregory calls attention to such occurrences in the Navajo Reservation (Gregory, 1917, p. 132). The writer has observed a similar condition in the Fort Bayard Military Reservation, New Mexico, where reportedly grazing has been excluded or rigidly controlled during the last several decades (Fig. 4*c*). Similarly an inconsistency is apparent in the condition found in many valleys, where certain portions have cut while other parts have not, although all have been subjected to the same grazing use. In the San Simon Valley, for instance, only a few of the main tributaries are gullied, although the others have obviously been subjected to equal, if not more intense, grazing.

The literature on conservation is replete with descriptions of the deterioration of the western ranges that has occurred since livestock arrival, and most of it is based on the premise that stock alone has been responsible for the depletion (see especially Bailey, 1935; Cooperider and Hendricks, 1937; Forsling, 1931; Bailey *et al.*, 1934; Cottam, 1947). Much stress is placed on the descriptions of early explorers, who picture lush grass in contrast to the present barren conditions. These, however, can be considered fair comparisons only when they are made with due regard to precipitation experienced in the contrasting years. Occasional seasons of favorable rainfall still produce a cover approaching that described in the earlier accounts. That there has been a general deterioration is conceded, but the proof is not yet positive that it can be attributed to the effects of overgrazing alone.

FIG. 4(*a*). Showing lack of vegetative recovery in fenced plot located in Freeman Flat near Safford, Arizona. Grazing has been excluded for 14 years. Altitude 3,000 feet. Average annual precipitation about 10 inches. Photo taken October 1948.

FIG. 4(*b*). Shows excellent grass recovery in Steamboat demonstration area, Navajo Indian Reservation, west of Ganado, Arizona. Area reportedly barren in 1934. Grazing has been regulated but not excluded. Altitude 6,500 feet. Average annual precipitation about 16 inches. Photo taken September 1948.

FIG. 4(*c*). Sparse vegetation on Ft. Bayard Military Reservation near Silver City, New Mexico. Grazing has been strictly regulated for past several decades. Altitude 6,200 feet. Average annual precipitation 17 inches. Photo taken September 1948.

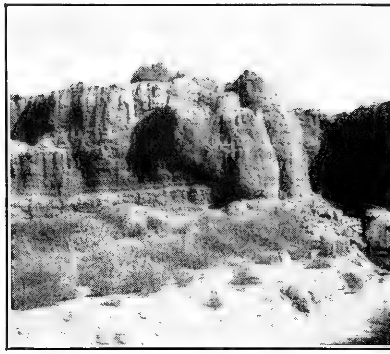

FIG. 5(*a*). One edge of a filled channel exposed in the bank of Chinle Wash gully near Chinle, Arizona.

FIG. 5(*b*). Outline of filled channel exposed in walls of San Simon gully, Arizona.

FIG. 5(*c*). Gradual filling in unnamed gully north of Shiprock, New Mexico. Looking downstream. Depth of fill at lower end more than 6 feet.

CLIMATIC CHANGES

Inquiry into changing climatic conditions, as a prerequisite to erosion, is beset by many uncertainties. To begin with, there is no precise standard for identification of such a change. It could be thought of as a reduction in rainfall, an increase in temperature, a change in rainfall distribution, or merely the occurrence of unusually severe droughts or exceptional floods. Recognition and evaluation of changes affecting any item or combination of items is difficult or impossible with the meager data available. Weather observations in the West, extending back to the 1880's or earlier, have been made at only a few stations. In general these show the expected yearly fluctuations in precipitation with no defined trend toward wet or dry cycles. Droughts and periods of excess precipitation, occurring during the past several centuries, have been identified and dated through tree-ring chronology (Schulman, 1945, pp. 42–47), but the indices used fail again to show definite cyclic trends.

Despite the lack of positive evidence supplied by precipitation data, investigations at various localities in the Southwest indicate erosion periods which can be attributed only to a climatic change toward drier conditions. In the gullied Jeddito Wash, located in the Hopi Indian Reservation, Arizona, Hack (1942) has identified three periods of deposition and erosion. Remains of extensive sand dunes, and other features closely associated with the erosion periods, lead to the conclusion that erosion occurred during a dry cycle. Albritton and Bryan (1939) describe a similar recurrence of deposition and erosion in western Texas, the dates of which can be rather closely correlated with those of Hack (1942, p. 68). Sayles and Antevs (1941, p. 39) recognize former periods of erosion in the Whitewater Creek in southern Arizona, and, in summarizing the evidence pointing to climatic change, Antevs (1948) states, "Thus the same climatic evolution from a moist-Pluvial which has grown slightly drier, is recorded by various conditions in several regions distributed from Trans-Pecos Texas northwestward to the Sierra Nevada and Oregon." Illustrations of previously filled gullies are shown in Fig. 5.

Thornthwaite *et al.* (1942, pp. 88–89), in discussing the evidence used by these investigators in identifying former erosion periods, argue that climatic change is unnecessary to explain them. Their interpretation is that upstream migration of discontinuous gullies within a valley would result in the same features as widespread erosion, including both terraces and buried channels. It is assumed that development of such gullies would cause waves of deposition to migrate slowly up-valley, thus leaving what appeared to be a continuous fill of the same age but which in reality would vary greatly in age in different reaches of the valley. Development of terraces would naturally be associated with this process. Likewise a subsequent gully, cut along the line of the buried discontinuous channel, would expose filled sections duplicating those found at present. Although this interpretation is logical in some respects, to accept it would simply mean admitting that erosion in past periods differed from that of the present only in extent. Under these conditions it hardly seems consistent to attribute one to natural causes, the other to overgrazing. Antevs has also pointed out this inconsistency (Antevs, 1948, p. 12).

From this brief mention of the investigations directed toward appraisal of the effect of climatic fluctuations on erosion, it should be apparent that much research is still needed before its full importance, as applicable to the erosion problem of the West, can be determined.

CORRECTIVE TREATMENT FOR GULLIES

No generally successful method of gully treatments which has proved capable of preventing both lateral and headward cutting has yet been devised. Even the task of arresting headcuts, where the treatment can be concentrated on a small area, has proved both difficult and expensive, and many efforts have ended in failure. The greater and more complex problem of stopping bank cutting where miles of raw, vertical walls composed of highly erodible alluvium are exposed is still more difficult of solution, and the final task of reversing the present phenomena to the extent of substituting aggradation for degradation in these narrow channels will doubtless prove most difficult of all.

To date, the program of treatment has followed two general lines: (1) reduction of grazing use, and (2) installation of control structures of various types. Unfortunately, in most instances, these were not combined, so the full effect of the two acting in unison cannot be evaluated.

Naturally, if it is assumed that overgrazing is responsible for erosion, the obvious treatment is reduction or complete exclusion of livestock from eroding areas. As such action directly affects the livestock industry, it raises questions of a social and political nature which have not yet been resolved. Livestock growers, although fully conscious of the erosion menace, are generally not convinced that their herds are completely responsible for it or that removal of them will effect a cure, and such reduction as has been accomplished has generally been with the idea of increasing forage rather than as a treatment for erosion.

Locally tracts have been fenced or otherwise protected to demonstrate the advantages of reduced grazing on both increased forage production and decreased erosion. The results vary widely, as indicated by Fig. 4, which shows typical demonstration areas. In some localities the recovery has been excellent; in others, insignificant. It is apparent from this that availability of moisture, condition of the soils, and other ecological factors may have as strong an influence on vegetative recovery as utilization.

Structural treatment was extensively used during the C.C.C. program, which lasted from the early 1930's to 1942. These structures were generally of simple design and, since the program was aimed at work relief, a large part represented hand labor. Most of the early treatment areas were confined to tributaries of the major channels or to areas in which smaller gullies had developed, and only occasionally was an effort made to treat or control the larger features. The structures utilized were of wide variety and included water spreaders of many different types, check dams, contour furrows and terraces, diversion and training dikes, and small to moderately large storage and silt-detention reservoirs (Fig. 6). Essentially the basic aim of the program was to induce vegetative recovery which would in turn furnish greater opportunity for percolation and thus reduce floods to safe and non-eroding rates. As there was no precedent for this type of treatment, much of it can be considered strictly experimental in nature, and failure in many instances to achieve the hoped-for results is not to be considered a reflection either on the designers or on the idea of land treatment. Future practices should benefit from these mistakes.

Appraisal of the results of the treatment programs on both erosion and revegetation presents, in general, a discouraging outlook. Detailed examinations by personnel of the U. S. Geological Survey of seven treated areas comprising a total of 5,600 acres located in the Upper Gila River in Arizona and New Mexico show that, of the 1,094 individual structures, 375 or 30 percent have failed for various reasons, the most prevalent being undercutting and piping in the foundations and lack of maintenance. More significant than the failures, however, which doubtless could be eliminated by a higher standard of construction and careful maintenance, is the lack of any discernible evidence of soil stabilization or vegetative recovery in areas controlled by structures that have not failed. In all cases vegetative recovery has been classed as unnoticeable or no different from adjacent untreated areas. Moreover, the treatment has had little effect in preventing soil movement or in reducing runoff crests to any appreciable extent. Old gullies and erosion scars have not healed, and in many instances new ones have developed.

It is obvious from these results that in the more arid areas, like that represented by the Upper Gila Basin, this type of treatment is of little value. The reasons for this are not so obvious, but apparently the flashy type of runoff produced by the higher intensity summer storms characteristic of this locality is greater than these small-dimensioned structures can cope with. Lack of vegetative recovery may be attributed to drought and erratic distribution of rainfall together with continuous grazing. Effect of the latter factor is hard to determine, but the fact that herds were not reduced to any appreciable extent reflects the lack of confidence of the stock grower in the success of this type of program. A more successful demonstration is needed before this confidence can be restored.

Recently the practice of water spreading has been greatly expanded, and in some instances it has been used on major gullies. Success of this treatment depends on complete diversion of flood flows onto a spreading area sufficiently large to absorb all the water, because, if any is allowed to return to the channel, new cutting immediately starts at the bank. One of the most successful installations of this type has been on the deep Polacca gully in the Hopi Reservation, Arizona, where water has been spread a distance of 15 miles below the point of diversion. Sand dunes, distributed along the bank, act as a natural barrier to prevent water from returning to the channel for part of the distance; training dikes parallel with and close to the channel have been constructed for the same purpose along the remaining part. Similarly treated areas located upstream on the Polacca Wash and in the tributary Wepo Wash utilize a system of dikes strategically placed so as to direct the water away from the channel at needed intervals. Other water-spreading areas using the same system are located in parts of the Tularosa Valley in New Mexico and in the Alzada district in the Little Missouri River basin in Montana.

Although the projects have not yet been in operation long enough to permit decisive evaluation, results to date appear to be promising particularly from the standpoint of range rehabilitation. Increase in forage as a result of water spreading has been of the order of several hundred percent in some reported instances—enough to justify considerable expenditures for such treatment.

The final effect this treatment will have on the gully has yet to be demonstrated. Naturally, erosion in the channel downstream from the point of diversion is stopped, but, since the supply of sediment is

FIG. 6(*a*). One type of erosion structure, utilized in C.C.C. program. Net wire spreader has caught silt but has failed to induce vegetative recovery. Freeman Flat area near Safford, Arizona. Structure built about 1938. Photo taken October 1948.

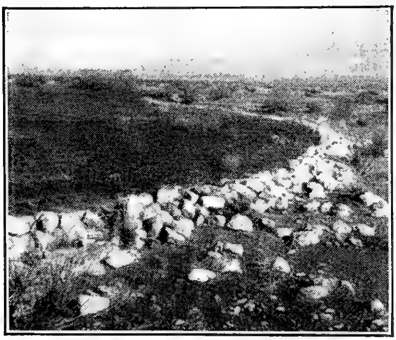

FIG. 6(*b*). Partially breached rock spreader built by C.C.C. about 1938. San Simon Valley near Rodeo, New Mexico. Photo shows slight increase in vegetation on alluvial fill behind spreader. Photo taken October 1948.

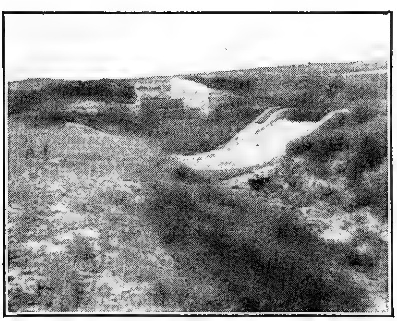

FIG. 6(*c*). Spillway and drop structure leading from spreader dike constructed by C.C.C. Steamboat demonstration area, Navajo Indian Reservation near Ganado, Arizona. Structures have prevented deepening of the channel but will soon fail unless repaired.

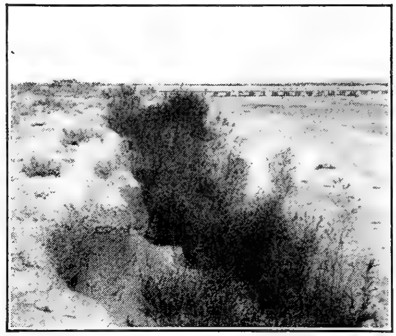

FIG. 7(*a*). Bank protection along Chinle Wash. Many Farms area near Chinle, Arizona. Ground water is within a few feet of the surface.

FIG. 7(*b*). Vigorous growth of cottonwood trees and willows form bank protection in Keams Canyon gully, Navajo Indian Reservation, near Keams Canyon, Arizona. Gully is 50 feet deep. Stream is perennial in this reach.

FIG. 7(*c*). Deposition induced by tetrahedrons with willows and other types of shrubs. Chinle Wash near Chinle, Arizona.

also cut off, no opportunity is afforded for the channel to fill except from bank caving or from wind deposition. The reservoir behind the diversion dam provides limited storage for sediment carried by the stream, but once this is filled the problem of sediment disposal again is met. As the very act of water spreading reduces the carrying capacity of the stream, an alluvial fan immediately begins to form at or near the diversion point. The tendency is for this fan to increase in height until a new gradient on which the stream can carry its sediment load is established. Unless a protective vegetative cover becomes established, gullying is likely to develop on this higher gradient. Evidence of this trend is already becoming apparent in some of the older installations.

One disadvantage in water spreading is the loss of water occasioned by the spreading operation. Where supplies are ample for all needs, the point has no significance, and the right to spread will probably never be contested. On the other hand, however, should the practice of spreading become widespread in the Colorado River Basin with its limited supply, compared with existing and planned demands, it is quite easy to visualize strong objections being raised from downstream users. This precise situation developed on the Gila River in 1940, where irrigators in the San Carlos District supplied from the San Carlos Reservoir took the stand that the C.C.C. structures in the Safford and Duncan valleys were interfering with and reducing the normal runoff on the river. A special investigation authorized by the National Resources Planning Board * showed that the supposed reductions were more fancied than real, and thus not significant enough to warrant action, but the attitude of irrigators, in this instance, is indicative of the developing conflict for the use of water in western streams, no matter for what purpose, and any gully treatment or other type of conservation program must eventually, if not at present, give it consideration.

Efforts to prevent bank cutting and meandering in gullies has been tried on a limited scale and with varying success in a number of localities. Possibly greatest progress has been achieved in the Navajo Indian Reservation, where several miles of the Chinle Wash and Keams Canyon Wash gullies have been stabilized against widening under the conditions of flow thus far experienced. The treatment consists essentially of tree and willow plantings, some started without pro-

* Upper Gila River Report by the Technical Committee, National Resources Planning Board, Oct. 21, 1940, unpublished.

tection, others in association with tetrahedrons or other types of revetments. Figure 7 shows views of this treatment.

Although plantings offer certainly the cheapest and most promising field for this type of treatment, their use is limited to reaches where water is available for plant growth. This condition automatically excludes the vast majority of gullies from treatment of this sort, because most are cut in dry valley floors where the surface flow is too infrequent or ground water is too deep to support vegetation. Protection of banks in this type of gully remains for future solution.

A permanent solution of the overall problem presented by gullying in the western valleys can be achieved only where the gullies have been refilled and the valley floors restored to a condition approaching that existing before cutting occurred. This involves substituting aggradation for degradation within the channels themselves. In theory, as shown by Lobeck (1939, p. 168), the construction of a barrier to the height of the gully wall or slightly above should accomplish this, and, given time enough, perhaps it will. However, the results observed at numerous barriers, some of which have been installed for more than 20 years, furnish little promise for results within the foreseeable future.

Surveys conducted by the Soil Conservation Service * and the Geological Survey † to determine the gradient assumed by the fill above these barriers show a minimum of 0.07 percent or 3.7 feet per mile and a maximum of 0.76 percent or 40 feet per mile. These results apply to localities where the fill was composed of sand and silt only. In every case the gradient was less than 50 percent of the slope of the valley floor. Textural analyses of the sediments constituting the deposits failed to furnish any information about the disparity in the fill gradients, although, as might be expected, coarser sediments were generally associated with the steeper slopes.

Numerous observations indicate that vegetation forms one of the most effective traps for sediment, and, where it is dense enough, even fine-textured sediments will deposit on the floors of gullies. This action is demonstrated in the Chinle and Keams Canyon washes, previously mentioned, where as much as several feet of sediment has been deposited within the fringe of trees and willows planted primarily for bank protection. Gradual filling of numerous gullies tributary to the Powder River near Broadus, Montana, has been noted during the past few years of favorable precipitation, during which dense growths of

* G. A. Kaetz and L. R. Rich. *Report of surveys to determine grades of deposition above silt and gravel barriers,* U. S. Soil Conservation Service manuscript, 1939.

† Information in U. S. Geological Survey file in Salt Lake City, Utah.

rose briers have become established on the gully floors. Figure 5*c* shows filling on the floor of a gully in northern New Mexico. Here a moderately dense growth of grass, weeds, and shrubs has been sufficient to trap silt and clay originating from an active headcut located a few hundred feet upstream. Deposition in this locality is of unusual significance in that it has occurred during a drought period when other gullies in the vicinity were actively degrading. Studies of this and other aggrading reaches will perhaps furnish information regarding methods that might be employed to increase the gradient of deposition behind barriers.

NEEDED RESEARCH ON GULLIES

Irrigation and stock raising constitute the backbone of industry in the western states. With both being jeopardized at a constantly increasing rate by gullying and other forms of erosion, research aimed at developing feasible methods of control is patently a necessity. To be successful this research will need to be directed into all elements of the problem, from geology and ecology to the practical phases of engineering and range management. The writer makes no pretense of being in a position to outline such a research completely, but on the basis of considerable experience within the area, the following generalized subjects are suggested as fundamental to the problem.

Because re-establishment of aggradation within the gullies and on the valley floors offers the only permanent cure for erosion, geologic studies should be undertaken to determine the conditions existing during previous periods of valley filling. This will involve all phases of the sediment history of the valley, from the initial weathering of the source rock through its transportation to final deposition and possible alteration since. Pertinent questions which need to be answered involve the factors that were most important in establishing former profiles of stream equilibrium: grade; magnitude of flow; sediment load; character of the sediments; vegetative cover on the watershed as a whole or more particularly on areas where aggradation took place. As reasonably accurate answers to these questions are found, comparisons will be possible with existing conditions under which streams are actively degrading. The same questions relative to factors influencing such action will again need to be answered, but with additional ones aimed at determining the possibilities of favorably altering these factors by engineering structures or land-management practices.

Information on the history of the eroding valleys, particularly with regard to the recurrence of degradational and depositional cycles, needs to be enlarged. If it can be shown that these periods were not local in extent but affected widespread areas simultaneously, and that they were related to some common cause such as increasing aridity of climate, of which the present might be an example, a long step will have been taken in formulating a plan of erosion treatment. As the record of the changes must be read from the sediments themselves, new techniques and standards for recognizing and evaluating the evidence must be developed. One urgent need at present is a method for determining the relationship between climate and the character of sediments deposited during a given period. Another is for criteria that can be used in interpreting climate by the evidence of alteration in the sediments since deposition. Each is fundamental in finding the causes of past changes in valley history.

Because vegetation is so closely allied to the erosion problem, the need for research, not only on its relation to sediment transportation but also on means of propagating vegetation, are evident. Among the pertinent questions are: What is the minimum density of various types of cover required to prevent erosion on the many different soils and slopes commonly found in western desert valleys? What minimum density is required to induce deposition under the same conditions? Is the normal precipitation in the area sufficient to maintain this density with or without grazing use? If not, what feasible measures, if any, including both engineering structures and changes in land-management practices, can be taken to insure protection of the most vulnerable localities?

These suggestions touch only broad phases of the research needed before the critical erosion problem of the West, of which gullying is the most prominent feature, can be approached with any hope of successful solution. The prosecution of this research will necessitate detailed inquiry into the many interrelated aspects of erosion, each of which will involve long, arduous, and expensive effort before the final answer is obtained.

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Part 4

APPLICATIONS INVOLVING NATURE OF CONSTITUENTS

Chapter 24

INFLUENCE OF SEDIMENTATION ON CONCRETE AGGREGATE

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Concrete aggregate, that is, the rock and sand that are mixed with cement to make concrete, may be natural sand and gravel, or quarried rock crushed to sand and gravel sizes, or any combination of crushed and natural material. Sand and gravel comprise slightly less than two thirds of the concrete aggregate produced annually in the United States. Quarried, sedimentary rock, predominantly limestone, will constitute about one fifth of the total production. The processes of sedimentation always influence and frequently control the development of the various properties that combine to determine the usefulness of either sand and gravel or sedimentary ledge rock as aggregate for concrete.

The remaining annual production is represented by non-sedimentary types, including crushed igneous and metamorphic rock. The latter category of aggregate is in no way influenced by processes of sedimentation and is therefore ignored in this presentation.

Concrete in service is subjected to various external conditions which may impose stress, strain, saturation, desiccation, chemical attack by aggressive solutions, abrasion, impact, and temperature changes conducive to expansion and contraction. Internal conditions inherent in the chemistry of the cement itself subject the constituents of concrete to additional rigors. In the first place, cement is an aggressively alkaline material capable of greater or lesser chemical interaction with any aggregate material. In the second place, the hydration involved in the setting of cement is accompanied by heat generation which, in large masses of concrete from which heat is dissipated very slowly, will cause significant expansion with attendant stresses and strains, followed ultimately by a contraction, with its own complement of stresses and strains, when cooling finally occurs.

The different constituents of concrete are chemically and physically heterogeneous. Cements differ widely in composition and in physical character and behavior, and the rock and sand comprising the aggregate—excluding certain monomineralic types, such as limestone or quartz—will generally contain a variety of minerals, each with its own physical and chemical characteristics and with its own unique response to environmental conditions.

These separate and diverse constituents of concrete react individually to the internal and external influences to which the concrete is subjected, and they interact with each other and thus determine its durability and serviceability and its appropriateness and effectiveness for its intended use. Inasmuch as aggregates normally comprise about 75 percent of concrete, their physical and chemical properties profoundly influence the overall character and behavior of any concrete mass.

Ideally, the selection of concrete aggregates should be based on a detailed appraisal of their chemical and physical properties, so that materials may be chosen that will react and interact harmoniously and compatibly and impart to the concrete properties consistent with its purpose. Deleterious reactions or incompatible interactions result inevitably in premature deterioration or ineffectual service.

Practically, it is not now possible in the manufacture of concrete to pay full deference to these considerations. In the first place, the variables involved are numerous and intricately interrelated, and the isolation of any separate variable for individual study, although practical on a research basis, is impractical as a routine, and suitable laboratory tests have not been standardized for general application. In the second place, in the present state of concrete technology there are many factors of uncertain and obscure significance, and various current hypotheses lack certain confirmation. Furthermore, the usefulness of concrete as a construction material depends in part on its relatively low cost. Economic considerations, therefore, prohibit costly beneficiation or the arbitrary rejection of a cheap local material and the costly importation of aggregate from a more distant source unless the advantages to be gained are assured and commensurate with the added expense.

Current research is rapidly resolving the remaining technical uncertainties in aggregate selection; and the most enlightened current practice involves the formulation and progressive revision of specifications and the development of acceptance tests that will exclude inappropriate materials unequivocally, no matter how cheaply they may be obtained. But additional research will be required to define entirely the properties that are admissible and inadmissible, and to develop simple tests which will discriminate conclusively between acceptable and unacceptable aggregate materials.

PROPERTIES OF CONCRETE AGGREGATE

One important set of properties that influence the quality or suitability of concrete aggregate includes: strength, hardness, compressibility, durability, elasticity, particle shape, surface texture, specific gravity, porosity, volume change with varying thermal or moisture conditions, presence or absence of deleterious impurities or coatings, mineralogic composition, and a variety of chemical properties related to the stability of the aggregates in the aggressively alkaline environment of concrete or their resistance to the agencies of natural weathering. These various properties apply to individual particles of aggregate. They may not always be equally important, their importance depending on the use, purpose, and environment for which the concrete is designed, but each influences the serviceability, durability, or cost of concrete for general or special purposes; and together they contribute fundamentally to the behavior of a concrete mass under different service conditions. For the benefit of readers unfamiliar with concrete technology these properties are summarized briefly in the appendix of this chapter from the standpoint of their significance to concrete. More complete discussion and extensive bibliographies may be found in American Society for Testing Materials (1948a, b, c), U. S. Bureau of Reclamation (1949), Rhoades and Mielenz (1946), Blanks (1949).

Another set of properties, related not to individual particles but to the overall assemblage of particles, includes minimum size, maximum size, size gradation, and degree of mineralogic or lithologic diversity. (See appendix of this chapter and ASTM, 1948b; U. S. Bureau of Reclamation, 1949; Twenhofel, 1932.)

A third set of properties, applying to whole deposits of aggregate, that influence the quantity of material available, the optimum method of excavation, the kind of beneficiation required, and like considerations, defines the adequacy of any aggregate source and the cost of aggregate production. This category of factors includes the area, depth, variability or stratification, overburden, topography, and depth to ground water (ASTM, 1948c; U. S. Bureau of Reclamation, 1949).

NATURAL SAND AND GRAVEL AGGREGATES

The properties of individual particles of sand and gravel (for example, surface texture) or of assemblages of particles (for example, grading), which determine suitability as aggregate, as well as the characteristics of deposits as a whole which control feasibility and economy of production, are all influenced by sedimentation and related processes; indeed, the character of a natural sand and gravel usually results almost wholly from (*a*) the kind of original or source material from which it was derived and (*b*) the modifying influence of its subsequent experiences as it was transported and deposited (Twenhofel, 1932).

PROCESSES OF SEDIMENTATION INFLUENCING SAND AND GRAVEL AGGREGATES

Sand and gravel, potentially useful as concrete aggregate, may be transported and deposited by water, wind, ice, or gravity, or by any combination of these agencies. Inasmuch as different mechanisms are involved in transportation and deposition by these various agencies, each will impart to the material involved certain characteristic and recognizable properties. However, although the transportation and deposition may differ both in mechanism and rigor, all these agencies influence the material transported and deposited through some combination of the following processes: (1) impact, abrasion, or crushing; (2) sorting; (3) weathering, leaching, and chemical reaction.

Weathering, leaching, and chemical reaction are not necessary accompaniments to sedimentation, but they frequently are inextricably associated or occur concurrently with it, and in such cases their consideration is essential to any complete understanding of the rock properties resulting as end products of the sedimentation process.

These actions occur conjointly, and the final properties imparted to a sand and gravel will be the summation of their combined effect; but certain of the resulting properties are most influenced by one or another of these actions, as indicated in the following examples.

Impact, abrasion, or crushing. This action, for example, is primarily responsible for modifying the initial shape of the particles in the direction of increased roundness; for reduction in the size of all particles, and sometimes in the elimination of all particles above a certain size; for the elimination of soft constituents that may have been present in the initial material; or for the roughening of surface texture.

Sorting incident to transportation and deposition. This action controls the grading of the sand and gravel, subject, of course, to the gradation of sizes furnished at the source, and it usually governs the maximum and minimum sizes of particles occurring in the final deposit. This action also influences the variability of the deposit, its stratification, and the thickness and kind of overburden.

Weathering, leaching, and chemical reaction. Through this action the strength or durability of the particles may be decreased, or the absorption increased through the leaching of soluble constituents or the chemical decomposition of vulnerable ingredients. Undesirable particles, if soluble or reactive, may be eliminated through solution, leaching, or chemical reaction; or the same processes may cause the formation of coatings about aggregate particles which may be innocuous if they are hard, chemically stable, and firmly adherent, but which may be deleterious if soft, chemically reactive, or loosely bonded. By a further extension of the same process particles may be cemented in a manner to hinder the economical exploitation of a deposit. Clay or other impurities may be formed as a consequence of the chemical decomposition of certain minerals (for example, feldspar); such clay may remain within the individual particles (contributing to volume change through wetting and drying) or accumulate as a separate component of the deposit and contribute to an excess in the very fine size grades.

Significance of "Source Material"

The final properties of a sediment, including those properties important in concrete aggregate, are strongly influenced by the kind and condition of the source material. Different source materials will be affected differently by the various sedimentation processes, and a sediment usually exhibits vestiges of initial properties—inherited characteristics, variously preserved and variously modified—as well as those superimposed during sedimentation.

The properties contributed by the parent rock are those related to the mineralogic and petrographic composition of the rock or its initial physical and chemical condition (ASTM, 1948a; Bureau of Reclamation, 1949; Rhoades and Mielenz, 1946). For instance, the strength or the elasticity of an individual particle of sand or gravel is primarily determined by its mineralogy and the textural relationships of the component minerals. The initial mineralogy and texture may be altered slightly or profoundly during transportation and deposition, but they will be preserved in some degree unless the particle is wholly decomposed or disintegrated; moreover, the initial mineralogy and texture largely define the reaction and resistance to the various modifying processes and thus influence the kind and extent of the modification that will occur.

For example, the shape of a sand or gravel particle is in part the result of attrition during transportation, but it is controlled also by the initial shape which in turn results from the spacing and patterns of joints and fractures in the parent rock. Similarly, the maximum size of particle in a gravel deposit will depend in part on attrition during transportation but can never exceed the dimensions of the particle originally supplied at the source, again a function of the spacing of joints or fractures. The mineralogy and petrography of the parent rock will also determine the initial clay content, which may be related to absorption and volume change under conditions of wetting and drying. The initial porosity of the rock is related to its internal texture. Surface texture may be related directly to the mineralogy and texture of the parent rock, if governed by cleavage planes, as in feldspar, or by the fracture form characteristic of certain minerals as, for instance, the conchoidal fracture of quartz, both of these surface textures, unless subsequently rendered rugose by leaching or attrition, being too smooth for development of optimum bond with cement.

The chemical characteristics of aggregate, although in part related to subsequent leaching, solution, weathering, and the like, which may attend the processes of sedimentation, are also in part controlled by the initial composition of the source material. Thus the mineralogy of the parent rock will dictate whether or not weakening, softening, increased porosity or absorption, or the development of secondary clay will be caused by these processes, and to what degree.

The most important chemical reaction which occurs between aggregate and cement in concrete, the so-called alkali-aggregate reaction, is usually the direct result of the mineralogy or petrography of the parent rock (ASTM, 1948a; Rhoades and Mielenz, 1946; McConnell *et al.*, 1948). The rocks and minerals susceptible to this type of reaction are the glassy volcanic rocks of acid to intermediate composition (rhyolites through andesites), such silica minerals as tridymite, opal, and chalcedony (and cherty rocks of which they are constituents), and probably a hydromica which occurs in some phyllitic rocks. These rock and mineral types, when exposed to the attack of the excess alkalies contained in a high-alkali cement, yield a silica gel that will imbibe water by osmosis and swell with the development of large, expansive pressures. Concrete so affected expands and cracks in an unsightly manner and not infrequently becomes unsafe or unserviceable. However, the initial reactive potentialities of an aggregate may be lessened by the processes of transportation and deposition, as, for example, through mixing and dilution with other rock types that are non-reactive; or a rock originally innocuous may become reactive by the addition of secondary opal or chalcedony as coatings or intergranular cement during sedimentation.

Many different geological formations may contribute to a sedimentary deposit and supply a large variety of rock types representing many different physical and chemical "source" conditions. Table 1 indicates the complex composition of a gravel deposit on the upper Missouri River. Such mixing of materials is most pronounced and complicated in the sediments of rivers draining large basins. Although a sand and gravel deposit occurring near the head of a river may contain a limited number of rock types, the complexity of the mineral and petrographic assemblage will increase downstream as each successive tributary contributes the rock types available within its own watershed. Contributions of sound rock by a tributary to a stream whose sand and gravel load is mainly composed of inferior material will naturally be beneficial; but one major tributary contributing a large amount of inferior or deleterious material may render deposits farther downstream less suitable as concrete aggregate (Spain and Rose, 1937).

This relationship is well illustrated by the Colorado River between Hoover Dam and Parker Dam. Sand and gravel obtained upstream in the vicinity of Hoover Dam contain a complex assemblage of rock types, some of which are susceptible to alkali-aggregate reaction. However, the quantity of reactive types at this point is small, and Hoover Dam concrete containing this aggregate exhibits no distress from alkali-aggregate reaction after 20 years of service. The Colorado River below Hoover Dam traverses terrain that is predominantly volcanic, and its sand and gravel become progressively enriched in deleterious volcanic rocks. At Davis Dam, 67 miles downstream, the sand and gravel are sufficiently reactive that special measures were required (use of low-alkali cement and pozzolanic admixtures) to forestall alkali reaction in the concrete. Farther downstream (156 miles below Hoover Dam) Bill Williams River contributes copious amounts of highly reactive aggregates—mainly andesites and rhyolites. Parker, Gene Wash, and Copper Basin dams built in this vicinity, and using local aggregate and high-alkali cement, exhibited extreme evidences of alkali reaction within 2 years after their completion.

Any initial characteristic of a source material may be either improved or impaired by the rigors of sedimentary transportation and deposition. For example, as previously noted, improvement can result through the elimination of soft particles or the rounding of particles

TABLE 1

PARTIAL PETROGRAPHIC ANALYSES OF GRAVEL FROM MISSOURI RIVER INVESTIGATED FOR CANYON FERRY DAM, MONTANA

Percentage by Weight

Rock Types	Drill Hole No. 3, 22 to 30 ft.		Drill Hole No. 5, 0 to 21 ft.		Description of Rock Types	Physical Quality	Chemical Quality
	1½″ to ¾″	¾″ to ⅜″	1½″ to ¾″	¾″ to ⅜″			
Quartzites	0.9	1.8	5.0	1.8	Hard, fresh, fine-grained	Good	Innocuous
Slightly weathered	30.0	27.1	34.6	21.2	Hard, quartzose sandstones to quartzites	Satisfactory	Innocuous
Moderately weathered	2.8	4.5	1.7	2.0	Porous, slightly friable	Fair	Innocuous
Deeply weathered	*	*	*	*	Friable, porous	Poor	Innocuous
Granites	19.0	7.8	11.4	16.0	Hard, aplitic to coarse-grained, mostly biotite granite	Satisfactory	Innocuous
Moderately weathered	6.0	3.6	1.3	...	Slightly friable, some slightly fractured	Fair	Innocuous
Deeply weathered	1.2	1.6	...	2.0	Crumbly, fractured	Poor	Innocuous
Basalts	...	...	3.2	...	Hard, fresh, fine-grained	Good	Innocuous
Slightly weathered	19.6	18.7	13.5	21.7	Hard, glassy to fine-grained, some vesicular	Satisfactory	Innocuous
Moderately weathered	...	...	...	0.4	Firm, slightly porous	Fair	Innocuous
Gabbros	*	*	*	*	Fresh to slightly weathered, medium-grained	Satisfactory	Innocuous
Weathered	*	*	*	*	Firm, moderately weathered, coarse-grained, serpentinized	Fair	Innocuous
Argillites	2.8	...	9.4	9.7	Hard, very fine-grained, dense, slightly weathered	Satisfactory	Innocuous
Weathered	2.5	6.9	...	1.4	Firm, moderately weathered, hard shale and argillite	Fair	Innocuous
Deeply weathered	...	8.0	...	1.0	Friable, very porous, some platy material	Poor	Innocuous
Hornblende diorites	*	*	*	*	Slightly to moderately weathered, medium-grained, hard	Satisfactory	Innocuous
Weathered	*	*	*	*	Moderately weathered, slightly friable, slightly porous	Fair	Innocuous
Limestones	3.1	3.6	0.6	5.1	Hard, fine-grained, fresh to slightly weathered	Satisfactory	Innocuous
Weathered	*	*	*	*	Firm, moderately weathered, fine-grained, slightly porous	Fair	Innocuous
Deeply weathered	1.1	2.6	0.3	1.0	Friable, very porous	Poor	Innocuous
Chalcedonic	*	*	*	*	Slightly to moderately weathered, chalcedonic, hard	Satisfactory	Deleterious [1]
Andesites	3.4	...	...	...	Slightly to moderately weathered, porphyritic, hard	Satisfactory	Deleterious [1]
Deeply weathered	0.8	...	...	...	Friable, fractured, porous	Poor	Deleterious [1]
Metaandesites	2.8	1.5	5.5	2.6	Hard, slightly to moderately weathered	Satisfactory	Innocuous
Weathered	*	*	*	*	Firm, moderately weathered, slightly porous	Fair	Innocuous
Deeply weathered	*	*	*	*	Friable, porous	Poor	Innocuous
Rhyolites	...	...	5.3	2.2	Hard, microcrystalline, slightly porous	Satisfactory	Deleterious [1]
Weathered	1.2	0.7	...	...	Firm, moderately weathered, slightly porous	Fair	Deleterious [1]
Deeply weathered	...	0.8	...	...	Friable, very porous	Poor	Deleterious [1]
Dacites	...	...	...	2.0	Slightly to moderately weathered, hard, glassy	Satisfactory	Deleterious [1]
Weathered	...	6.2	...	2.6	Firm, moderately weathered, glassy	Fair	Deleterious [1]
Deeply weathered	...	...	...	0.8	Friable, porous, fractured	Poor	Deleterious [1]
Cherts	2.8	3.6	8.2	6.5	Hard, fine-grained, chalcedonic	Satisfactory	Deleterious [1]
Weathered	...	1.0	...	...	Firm, moderately weathered, broken, chalcedonic	Fair	Deleterious [1]
Deeply weathered	*	*	*	*	Chalk-covered, porous, poor bond	Poor	Deleterious [1]

* These rock types are present in gravel samples from other drill holes in the same area.
[1] Deleterious with high-alkali cement.

during transportation, or through the roughening of surface textures. But the strength of particles may be reduced by leaching or by the loosening of initial microfractures through impact. The overall grading may improve downstream through the abrasive reduction of coarse sizes and the fortification of finer sizes which might otherwise be deficient in quantity, but the same processes may impair the quality of the gravel for use as concrete aggregate through so stringent a reduction of the coarse particles as to leave the gravel deficient in the larger sizes required for economical concrete design (ASTM, 1948b). Quality may be impaired through mixing with unsuitable rock types, but similar processes may be beneficial if inferior materials are "diluted" by the addition of sounder material from tributary streams. Usually improvement of certain characteristics accompanies impairment in others. In any event the end result will be the summation of effects of the various mechanisms of transportation and deposition as they impinge on the different rocks and minerals—with their various responses and reactions—that are supplied by the parent source.

TYPICAL OCCURRENCES OF NATURAL AGGREGATES

Potential sources of natural aggregates may be classified as river and stream deposits, talus deposits, wind-blown sand, glacial deposits, marine deposits, and residual deposits. A given area may contain several of these types of deposits or may contain only a few or no more than one. Geographical location strongly influences the type of deposit available for aggregate production and the character of aggregate in general use in any region (ASTM, 1948d; Thoenen, 1932).

River and Stream Deposits

Deposits in river channels. Deposits of sand and gravel occurring in channels of rivers and streams will be characterized generally by rounded particles distributed with some uniformity throughout the various size grades. Although large differences in gradation occur from deposit to deposit, as well as differences in the maximum size represented, deposits in the channels of gravel-bearing streams can usually be found which will satisfy the gradation requirements necessary for concrete design or can be made satisfactory in this respect by only moderate processing. Figure 1 indicates a gradation recommended by the American Society for Testing Materials (ASTM Designation C33-46). Superimposed on the same figure is a curve showing the gradation of natural sand and gravel obtained from the North Platte River near Kortes Dam site. In this instance, a gradation suitable for the manufacture of concrete was obtained by simple screening to effect the final grading shown. More elaborate processing may be required in other places: sands and gravels in the Colorado River at the "Wahweap" deposit near Glen Canyon Dam site, for example, contain the fine sizes in such excess that some 40 percent more sand than is re-

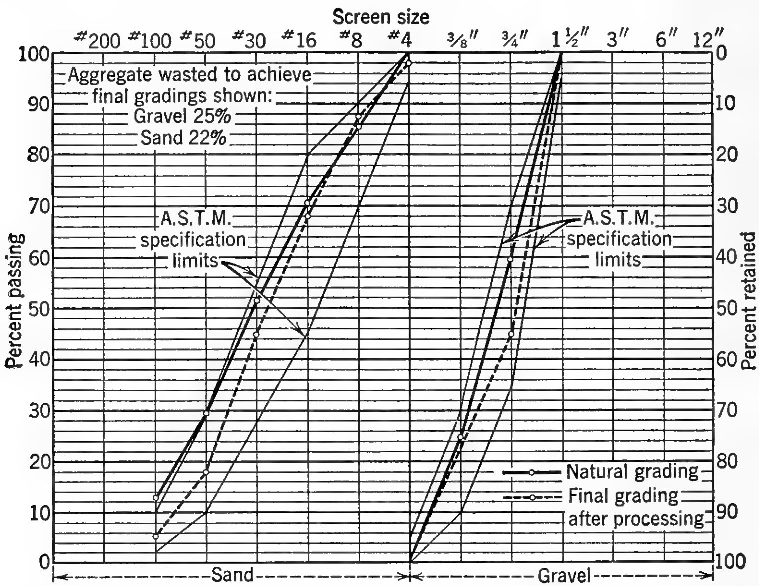

FIG. 1. Comparison of gradings of natural and processed aggregates with ASTM specification limits. (Aggregate from North Platte River investigated for Kortes Dam, Wyoming.)

quired must be processed and discarded in order to produce the requisite quantity of coarser material.

Attrition has had the effect in the Missouri Basin states, Kansas, Nebraska, and South Dakota, of eliminating entirely the coarse-gravel fraction of the river gravels (Scholer and Gibson). These gravels, derived initially from the Rocky Mountain area to the west, contain few, if any, particles over 1½ inches in size at any location east of the Colorado state line, although to the west coarser materials become increasingly abundant, and near the front of the mountains the gravels are fully graded.

River transportation normally causes a concentration of hard and firm particles through the selective elimination of softer materials by attrition. However, the strength and hardness of the particles are related closely to the source material from which the sediment was derived and to the distance the material may have been transported. For example, the comparatively hard and firm gravels of the Colorado River above the mouth of the tributary Dolores River, in the vicinity of Dewey Dam site (Utah) contrast sharply with the gravels downstream from the mouth of the Dolores, because of the large quantity of soft sandstone contributed to the main stream by that tributary. Farther downstream the soft Dolores sandstone is progressively reduced in quantity.

Improvement of surface texture also results from the attrition, impact, and abrasion incident to river transportation, so that river gravels will normally possess rugose surface textures conducive to good bond with cement. However, if large quantities of the pebbles that are furnished to the stream possess potential planes of breakage, as along cleavages, the impact and jostling during transportation may promote the division of larger pieces into smaller ones with comparatively smooth surfaces.

It must not be overlooked that the environment of river transportation and deposition is conducive to leaching of soft or soluble materials or to chemical reaction with materials susceptible to decomposition. These processes can aid the processes of mechanical attrition in promoting the selective concentration of hard and firm particles, but in other cases they can cause softening or weakening of particles that would be relatively invulnerable to mechanical attack alone.

The field occurrence of river-channel deposits on the upper Missouri River is illustrated in Fig. 2 (see also the petrographic analysis, Table 1).

River terraces. River-terrace deposits possess the general characteristics of river-channel deposits and are widely used for concrete aggregate. Terrace deposits, in many places, are exploited more economically than channel deposits, since, because of their higher topographic positions, they are normally not so subject to the production difficulties attending shallow ground water. In some areas, as along certain reaches of the Colorado River in Texas, the rivers themselves are not now transporting gravelly material, but gravels may, nonetheless, be found in terraces mantling the highlands where they were deposited by gravel-bearing streams of earlier times.

Terrace deposits commonly, although not universally, differ from channel deposits in exhibiting a greater prevalence of secondary coating or cementation of particles. Coatings resulting from the action of ground water, or waters infiltrating from the surface, may permeate the entire thickness of a deposit, but commonly (particularly in arid regions) they are associated with transpiration of moisture toward the surface and are most prevalent in the upper few feet. Concentrated deposition in the upper layers of a deposit may cause the formation of cemented layers that hinder excavation.

The most common coatings are calcium carbonate and, inasmuch as this material is chemically innocuous, they may in no wise impair the quality of aggregate if they are firm and tightly adherent to the

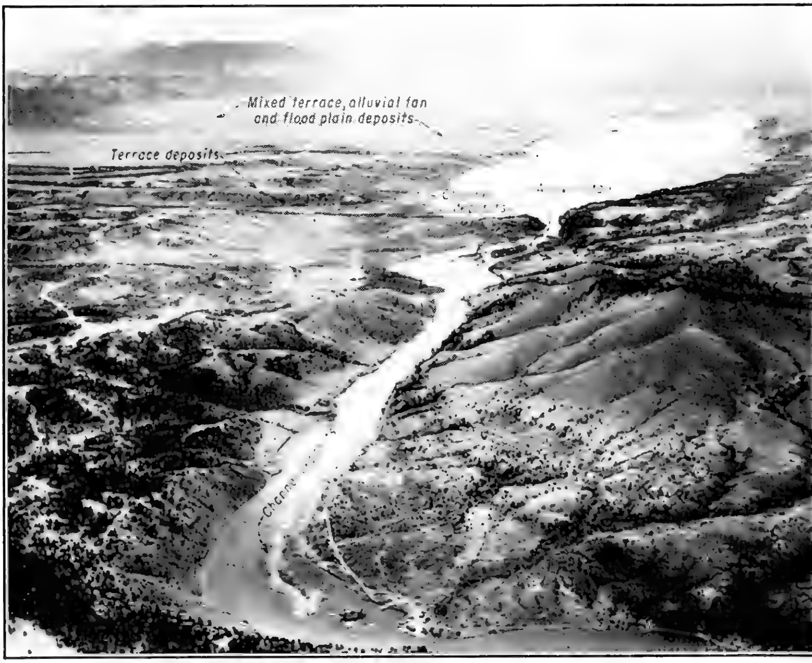

Fig. 2. Deposits of natural sand and gravel on the Missouri River near Canyon Ferry Dam site, Montana.

particles. Siliceous coatings—opaline or chalcedonic—are chemically reactive with alkalies in cement, and, no matter how firm and adherent, they will be detrimental to concrete unless used with cements low in alkalies (ASTM, 1948a; McConnell *et al.*, 1948). Coatings composed of iron oxide, manganese oxide, or gypsum are not uncommon. Gypsum coatings, being soluble and pulverulent, are detrimental, but they are often removed by normal washing and screening. In many places, as at Davis Dam (Colorado River, Arizona-Nevada) the upper several feet of a terrace deposit must be removed and discarded because of deleterious coatings or cemented layers.

Terraces frequently exhibit postdepositional weathering. Extreme weathering may render a terrace deposit entirely unsuitable for use as aggregate through decomposition of the individual particles. Terraces in some parts of the Columbia River Basin, for example, were formed at two different periods; in some localities the older and younger terrace materials appear to occur in continuous sequence and are not distinguishable through superficial observation, nor is the contact between them clearly discernible. In the investigation of these materials to determine their suitability for concrete, anomalous and conflicting results arose from a failure to distinguish between the older and younger materials. Subsequent studies disclosed that durable concrete may be made of the firm and hard basaltic particles comprising the younger terrace deposit, whereas the older, underlying material, which is similar in lithology and appearance, is composed of incipiently decomposed particles unsuitable for use in concrete. Typical gravel terraces are shown in Fig. 2.

Flood-plain deposits. Flood-plain deposits are characterized by variable and heterogeneous gradations. True flood-plain deposits caused by the periodic overflow of a stream from its normal channel are usually deficient in material larger than sand and hence have only a limited usefulness as concrete aggregate. Frequently such material mantles the upper surfaces of flood plains but is underlain by heterogeneous assortments of sand and gravel deposited in former times as the river meandered randomwise from side to side. When favorable size gradations are found in flood-plain deposits, they are entirely suitable for aggregate and possess the same general character as channel or terrace deposits. The flood-plain deposits shown in Fig. 2 are mixed with terrace and alluvial-fan deposits. They occur more typically in the broad valleys of more mature rivers.

Alluvial fans and cones. The principal characteristics of alluvial fan or cone deposits, particularly in arid regions, are heterogeneity and angularity. Since they were formed by successive torrential downpours with brief but violent runoff, and since the volume and velocity of runoff differed from storm to storm, the deposits are usually rudely layered into zones ranging from very fine material to very coarse; and the transportation, although frequently violent, is usually too quick and too short for the development of rounded particles. Alluvial fans and cones deposited by intermittent streams may contain material suitable for the production of concrete but usually require elaborate beneficiation, including screening, and possibly other measures such as blending with imported materials to fortify certain deficient size grades.

The alluvial fans shown in Fig. 2 were deposited under semi-humid conditions. A more striking series of alluvial cones and fans, typical of arid regions, is illustrated in Fig. 3.

Alluvial fans similar to those shown in Fig. 3 occur along the Boulder-Kingman (Arizona) highway, and they were investigated in connection with postconstruction activities at Hoover Dam. These fans disclosed the following characteristics: (*a*) Individual particles

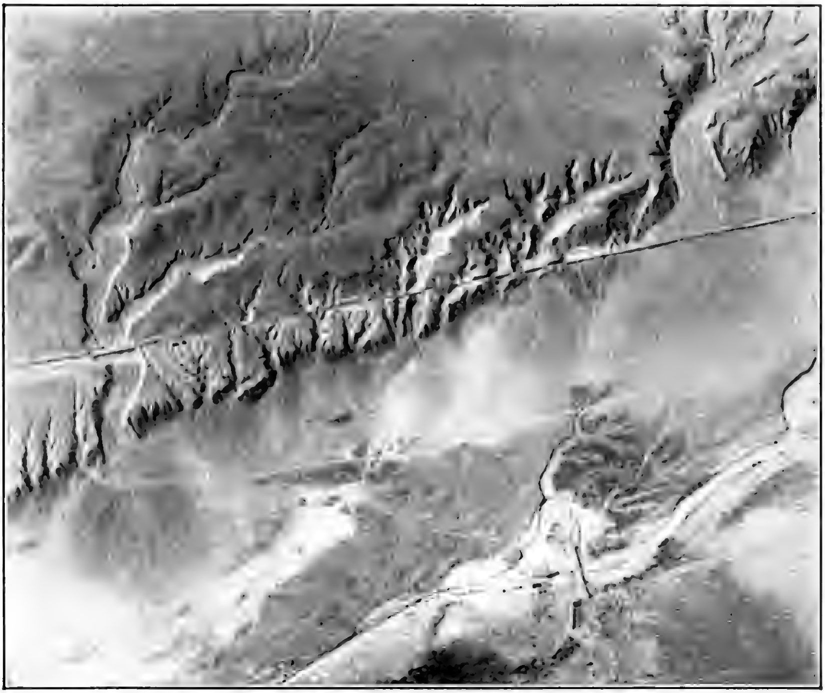

FIG 3. Alluvial cones and fans formed under arid conditions near Muddy River, Nevada.

are angular, having been transported quickly and only a short distance from the source material. (*b*) The deposit is composed of a limited number of rock types—those rock types that occur on the ridge at the head of the dry washes. (*c*) All sizes, including the sands, are essentially of the same composition, there having been no selective concentration of the more durable types. (The softer materials occur in proportion approaching their original proportion in the parent rock.) (*d*) The deposit is heterogeneous as to grading within layers and from layer to layer.

It was determined that this material would be suitable as concrete aggregate if locations and levels were chosen to avoid extremely coarse or extremely fine gradations, and if screening and washing were done thoroughly and with care. But the resulting concrete would be harsh and difficultly workable because of the angular nature of the individual particles.

Talus Deposits

Talus deposits formed by gravity at the bottoms of steep slopes are usually composed of a single rock type or a limited number of rock types—the types that occur on the upper part of the slopes—which have accumulated as particles ranging from very fine to extremely large, of angular and irregular shape, and with a minimum of orderly distribution of the various sizes. Such deposits represent, in effect, simply the original parent rock broken into fragments but otherwise deposited with little of the rounding, sorting, or segregating actions that characterize to a greater or lesser extent most of the other agencies of sedimentary transportation.

If the parent rock possesses characteristics suitable as concrete aggregate, the talus deposits will usually be suitable but will require the crushing and other beneficiation normally applied to quarried rock. Inasmuch as the rock has been fragmented by natural processes, it may on occasion be more economical to produce aggregate from a talus accumulation than from the parent-rock outcrop, from which the fragments would have to be produced artificially by blasting. In some cases the spacing and pattern of joints in the parent rock have controlled the maximum size of fragment that will form in a talus deposit, and in this way economical production may be facilitated through simplification of the plant installation required for crushing and related processing.

Four talus deposits have been recently investigated as possible sources of concrete aggregate: a granodiorite accumulation on the slopes of Ragged Mountain north of Spring Creek Dam site (Colorado); andesite porphyry on the slopes at Platoro Dam site (Colorado); and rhyolite from Sundance Mountain and phonolite porphyry from Missouri Butte (Fig. 4), both in the vicinity of Keyhole Dam site (Wyoming). It was found that these materials would make satisfactory concrete but that, because of the expensive processing required, the importation of river gravel and sand from other areas would be more economical.

Wind-Blown Sand

The extreme rigor of transportation by wind frequently results in the preservation of only the hardest and most durable rock and mineral types. Hence wind-blown sands, by and large, are composed predominantly of quartz. The grains are well-rounded and concentrated in a few size grades which reflect the average transporting capacity of the prevailing winds of the area. Such sands are useful in concrete aggregate only for "blending" to augment other aggregates which are deficient in the finer size grades. A typical wind-blown sand, occurring near Pot Holes Dam site, Columbia Basin (Washington) is shown in Fig. 5.

The gradation and composition of a typical wind-blown sand from near Kortes Dam (Wyoming) is shown in Table 2, sample A. A deposit of wind-blown sand occurring in the Columbia Basin (Washington) is noteworthy by reason of its mineralogic and petrographic composition (sample B). Its heterogeneous composition results from a predominantly local derivation from the Columbia Basin plateau lavas which comprise the prevailing bedrock. However, sample C, another blowsand from the same general area (near the Pasco Pumping Plant, Columbia Basin, Washington) exhibits quite a different composition,

TABLE 2

GRAIN SIZE OF WIND-BLOWN SANDS

Sieve Size	Diameter	A		B		C	
		Retained	Cumulative	Retained	Cumulative	Retained	Cumulative
	microns	%	%	%	%	%	%
16	1,190	0	0	0	0	0	0
30	590	0	0	0	0	5	5
50	300	4	4	9	9	6	11
100	150	50	54	76	85	9	20
Pan	...	46	100	15	100	80	100

A. Kortes Dam area, Wyoming. Mainly quartz and feldspar; some amphibole, mica, chlorite, chert, limestone, and siltstone.

B. Columbia Basin, Washington. Derived from lavas. Composition is plagioclase feldspar, with smaller amounts of basaltic glass, basalt, quartz, olivine, acidic glass, rhyolite, and opal.

C. Pasco Pumping Plant area, Washington, near sample B. Derived from marine and glacial sediments that mantle adjacent Pasco slope. Composition is mainly quartz, feldspar, and muscovite.

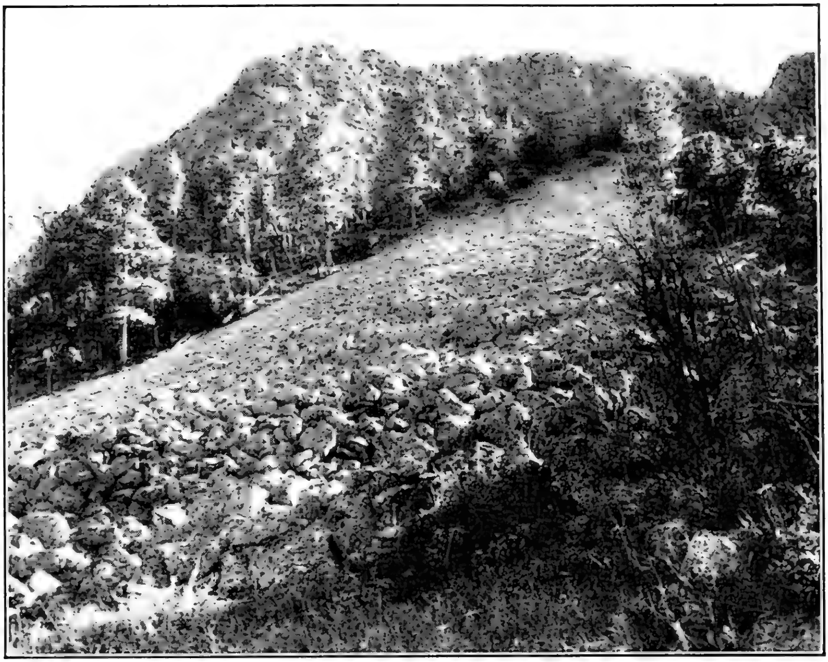

Fig. 4. Talus deposit at Missouri Butte, Wyoming.

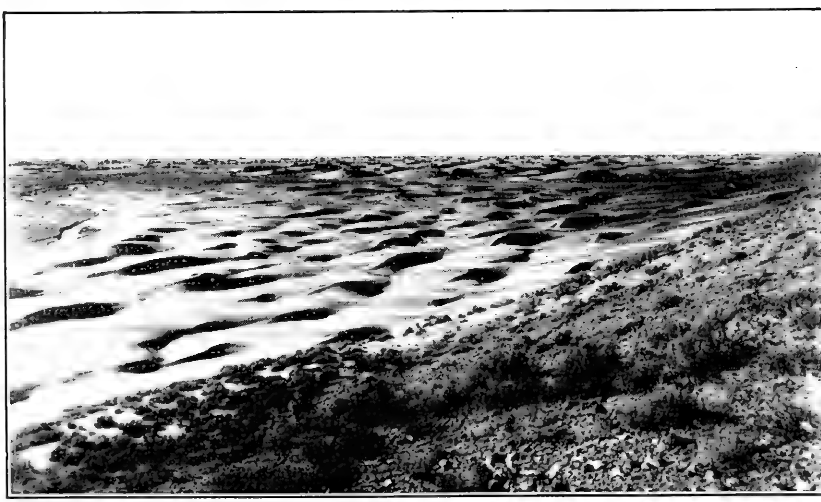

Fig. 5. Wind-blown sand near Pot Holes Dam, Columbia Basin, Washington.

being derived from the marine and glacial sediments that mantle the adjacent Pasco slope.

Deposits of volcanic ash and pumicite may be considered a special category of wind-blown sand. Glassy, volcanic tuff is useful as pozzolanic admixture with cement to impart certain desirable characteristics to concrete (Lea and Desch, 1935; Lea, 1938). For this purpose the materials should possess a fineness comparable to that of cement (as a rough index, at least 90 percent of the material should pass a 325-mesh sieve). Some pumicites are prevailingly of this fine size as, for instance, the extensive accumulations of pumicite in the vicinity of Friant, California, from which material was obtained for use in Friant Dam. If a deposit contains material prevailingly coarser than this size or if it is not readily pulverulent, it must be pulverized artificially; the additional cost of such processing is a frequent deterrent to the use of any given deposit of pumiceous material.

Pumice and scoria in coarser sizes are coming into increasing use as aggregate for the construction of special-purpose concrete, as in "cinder-block" construction or in the fabrication of acoustical or insulating concrete (Price and Cordon, 1949).

Glacial Deposits

Glacial deposits in the form of moraines, or tills, are typically characterized by extremely heterogeneous grading, frequently with large boulders and fine rock flour intimately admixed. Individual particles may be smooth or even somewhat rounded, but angular or subangular particle shapes are common. Glacial deposits normally exhibit some selective concentration of the harder rock types, but softer materials frequently are preserved through incorporation within the ice mass itself, where they are shielded from the intense abrasion and crushing that generally characterize glacial transportation. The glacial environment discourages extreme chemical alteration and thus inhibits the selective removal of materials which are soluble or susceptible to chemical decomposition. Thus, whereas firm particles may be preserved from the weathering and decomposition to which they might be susceptible in other sedimentary environments, soluble or chemically unstable materials may be preserved to the detriment of the deposit for use as concrete aggregate.

Certain areas of the United States are extensively mantled with glacial deposits and must rely on this source for concrete aggregate (ASTM, 1948d). However, such deposits usually require expensive beneficiation. Elaborate screening may be required to correct the grading, and the necessity of wasting large amounts of oversized and undersized material frequently involves the handling of much excess material for the production of a given quantity of aggregate. In deposits that contain large boulders the expense of processing is further increased. Where crushing of the oversized material is necessary to augment finer size grades, the expense is again increased.

Large accumulations of glacial erratic boulders may sometimes be used for concrete aggregate. In such cases the boulders are collected, crushed and screened in the same manner as though they were quarried rock. This procedure is economically feasible only in exceptional cases.

In contrast to true glacial deposits, glaciofluvial deposits are widely used as concrete aggregate. Only moderate reworking of glacial materials by fluvial agencies may suffice to form deposits comparable to true river sands and gravels.

Marine Sands and Gravels

Marine sands and gravels are typically characterized by hard, firm particles as a consequence of the extreme natural selection of the durable and elimination of the non-durable materials consequent to the winnowing action by waves and currents on a beach. The particles usually are very well-rounded and restricted to a narrow range of size grades. Marine sands and gravels are not widely used as concrete aggregate, but where available in sufficient thickness and extent for economical production and where proper gradations may be obtained by no more elaborate processing than is economically feasible, aggregate of excellent quality can be produced. These conditions may be found in thick terraces lying above the level of the present shore. Such deposits not uncommonly exhibit vertical variations of grain size from layer to layer, but selective excavation may be feasible by which is removed material which possesses an approximation of the gradation required, thus minimizing the amount of artificial processing that must be done.

Beach sands frequently exhibit characteristics similar to wind-blown sand, or indeed may owe their origin as much or more to the action of the wind as to the action of ocean waves and currents. These materials, like wind-blown sand, discussed previously, are suitable for use as blending sands in combination with other aggregates.

Sands and gravels occurring on beaches may be impregnated with deleterious salts and thus require rigorous washing. Such salts may have been entirely removed from older terrace deposits through leaching by surface and subsurface waters.

Coral and algal reef materials, such as occur profusely in the South Pacific, have had extensive local use in the production of concrete, but the special considerations and techniques involved in this class of concrete construction are beyond the scope of this discussion (Rasmusson, 1946).

Residual Deposits

Residual materials remaining in an area as the end products of weathering and erosion are rarely usable as concrete aggregate. Although they owe their existence to their durability and therefore are frequently hard and firm, they are normally ungraded in size and usually limited in quantity. Characteristically, they are admixed with substances unsuitable for the production of concrete aggregate.

Boulders of chalcedonic siltstone occurring over a considerable area in southwestern North Dakota and northwestern South Dakota furnish an example of the occasional usefulness of residual material. It was proposed that concrete aggregate for construction in that area be produced through the collection, crushing, and screening of these materials. Although laboratory tests indicated that satisfactory and durable concrete could be made with aggregates thus produced, excessive costs would be involved. The use of such material would be considered only in areas that lack material more suitable or more easily processed.

QUARRIED SEDIMENTARY ROCK

The suitability of a rock ledge for the production of concrete aggregate through quarrying and crushing depends on three general factors: (*a*) the intrinsic quality, physical and chemical, of the rock; (*b*) the uniformity of the available working face; and (*c*) textural and structural characteristics that influence the "crushing characteristics" of the rock (ideally, a rock should crush to firm particles, roughly equidimensional in shape, with a minimum of "powdering" or fragmentation into extremely fine sizes) (ASTM, 1948a).

The physical and chemical characteristics of quarried aggregate are those of the "source material" before the modifications—beneficial or harmful—which the processes of transportation and deposition would impose if the same material were to be transformed naturally into sand and gravel. Any beneficiation which a natural rock exposure may require to render it suitable as concrete aggregate must be applied artificially through crushing, screening, and washing. Different kinds of rocks will respond differently to such processing.

Ledge rocks are commonly variable in hardness because of localized leaching or cementation. Dolomites frequently are fractured, limestones frequently are leached and rendered porous along channelways penetrated by ground water. Concretionary structures representing local concentrations of mineral material deposited interstitially in sandstones, siltstones, or shales, or by replacement in limestone, occur sporadically in sedimentary formations. Limestones may contain interstitial clay, which renders the material susceptible to volume changes, or may contain chert lenses that are physically unsound or chemically reactive with the alkalies in cement, as in many localities in the southeastern United States.

The rock at a given quarry site may be massive and uniform in composition, or it may be stratified and composed of more than one rock type. Individual strata in a quarry may be hard or soft, porous or dense, jointed or unfractured. Limestones may be interbedded with shales, sandstones with siltstones, and quartzites with dolomites. Stratification may be vague or pronounced, the layers thick or thin. The thickness of layers may control the size and shape of the aggregate produced: rocks with thin stratification or lamellar structure will crush into planar or elongated pieces. Limestone may possess good crushing characteristics if dense and massive, but may produce particles of poor shape or an excess of fines if it has a lamellar "grain" or is closely fractured or highly clayey. Similarly sandstone may be hard or soft and thus crush well or poorly depending on the kind and amount of cement that binds the grains together.

These factors of petrography, texture, and structure are inherent in the sedimentary origins of rocks; the sedimentary processes by which a rock has formed will determine its intrinsic physical or chemical quality, the uniformity of the product which may be produced, and the practicability and ease with which it may be crushed and otherwise processed into aggregate suitable for concrete.

CONCRETE AGGREGATE RESEARCH

Past and current research on concrete aggregate has been a joint venture by engineers, chemists, physicists, and, recently, geologists. In the future, even more than in the past, research in concrete aggregate will call for the joint preoccupation of scientists and engineers of various specializations, with geologists playing an increasingly important role through analysis and interpretation of rock and mineral properties.

Concrete aggregates have been appraised and selected in the past primarily through the application of a series of empirical tests which measure, for instance, their specific gravity, absorption, abrasive resistance, soundness under freezing and thawing (or under the more rigorous and accelerated test with sodium or magnesium sulphate). Such tests have been correlated with field service over many years, and on the basis of this long experience they serve as guide lines for establishing specification limits and for the selection and rejection of proposed aggregate materials.

Today there is an increasing recognition by concrete technologists that these empirical tests, however useful they may have been for the practical purposes of the past, do not measure specifically the fundamental properties that define the "concrete-making" potentialities of rock materials (Blanks, 1949).

Surface texture, for example, is generally admitted to be highly significant in the fabrication of concrete because of its profound effect on the bond that will develop between an aggregate and the enclosing cement. But that property is never measured except in research investigations; there exists no test amenable to routine application by which roughness or smoothness of aggregate particles may be defined; there is no specification in which surface texture is used as a criterion for acceptance or rejection; and, indeed, there exists only a general and qualitative understanding of the effects of different kinds and degrees of surface texture. Many other properties of aggregates are understood in the same imperfect way: they are recognized as important; their effect on concrete can be gaged qualitatively; but their significance lacks, and badly needs, quantitative definition. Concrete technology requires that research of the future be directed toward the determination and elucidation of the properties of rocks and minerals, in terms of their quantitative significance to concrete.

An intimate knowledge of the inner character of rocks and minerals will be a first requisite to this research. This knowledge will be contributed chiefly by geologists and petrographers, with their special knowledge of the origins, histories, compositions, and textures on which the properties of rocks and minerals depend. But, if these contributions are to be directly useful, geologists and petrographers must also have insight into the concepts and technology of concrete. Research will progress only haltingly in this direction until the resources of the geological sciences are better mobilized for its prosecution—until more geologists acquire some competence in concrete technology, through academic training or practical experience, and become preoccupied with its problems.

APPENDIX

THE INFLUENCE ON CONCRETE OF VARIOUS PROPERTIES OF AGGREGATE

STRENGTH

The average crushing strength of rock types which would commonly be used as aggregate ranges from 10,000 to 30,000 pounds per square inch. Thus almost any rock possessing the other characteristics necessary for an aggregate will be far stronger than concrete we expect to make. High strength in rock can be beneficial to concrete subjected to stress, but the degree to which the strength and elasticity of the aggregate contribute those qualities to concrete is controlled largely by the integrity of the bond between cement and aggregate.

HARDNESS

In the mineralogic sense, hardness of particles depends wholly on the hardness of the constituents, not on the firmness with which the constituents are knit together. When used this way, a convenient distinction can be made between "weak" particles, which may be composed of either hard or soft grains that are weakly joined, and "soft" particles, which abrade easily however strongly the component grains may be joined. "Weakness" is never tolerable in concrete aggregate, but sometimes "softness," if not extreme, may be admissible. Weakness and softness are frequently associated, and a safe rule is to keep both weak and soft particles at a minimum; in special-purpose concrete (for example, abrasion-resistant concrete) aggregate must be both hard and strong.

COMPRESSIBILITY

The compressibility of aggregate particles strongly influences the drying shrinkage of concrete. A compressible particle is one that is reduced in volume by contraction of the surrounding cement paste as the concrete dries. As the cement paste shrinks, aggregate particles are thrown into compression; if the particle is strong and the cement-to-aggregate bond is good, shrinkage of the cement paste is restrained, and, consequently, the volume change of the concrete is inhibited. On the other hand, if the particle can be compressed, the drying shrinkage of the concrete will be high. Drying shrinkage of concrete will be increased greatly by particles that expand and contract with wetting and drying.

DURABILITY

Durability of concrete is its resistance to disintegration, volume change, or loss of strength and elasticity under conditions to which it is subjected.

Durability of concrete is controlled by the quality and gradation of the aggregate; the quality, composition, and fineness of the cement; the mix proportions; the methods of mixing, handling, placing, and curing; and the physical and chemical conditions that affect the concrete throughout its life. Aggregates which are physically unsound or chemically unstable, so that the particles disintegrate or change volume inordinately, can cause failure of concrete in service. Unsoundness or chemical instability of aggregate particles may be inherent to the constituent minerals or rock substances, or they may have been engendered by secondary processes of alteration.

Elasticity

Young's modulus of elasticity of rock commonly used for aggregate ranges from 2×10^6 to 15×10^6. Young's modulus of elasticity of hydrated neat cement paste ranges from about 1×10^6 to 4×10^6 as the load is sustained or rapidly applied and relieved. Although high elasticity is beneficial in particles used for ballast or road metal, aggregates of lower elasticity tend to reduce stress in concrete resulting from volume change or strain.

Particle Shape

Angular particles make "harsh" concrete that is difficultly workable; rounded particles contribute to smooth, workable mixes. High proportions of flat or elongated particles also decrease workability and hence necessitate the use of more sand, cement, and water to produce satisfactory concrete. Also, they pack poorly, thus reducing bulk weight and decreasing compressive strength. Moreover, flat particles tend to orient themselves horizontally in concrete, permitting the accumulation of water beneath them, a condition that prevents development of good bond on their lower surfaces.

Maximum and Minimum Gradation

The gradation of an aggregate is its particle-size distribution and is conveniently expressed as the percentage of material retained on standard screens. The grading of concrete aggregate has very pronounced influence on the workability of concrete and on the proportion of cement and water needed to produce concrete of desired quality. Because of economic considerations, variation in particle shape and texture, variation in different brands of cement, and variation in size and design of structures, no one gradation is satisfactory for all purposes. However, to be suitable for concrete manufacture, aggregate gradation must fall within certain limits in order to achieve satisfactory packing of the particles. In practice, the gradation of aggregate is controlled by specifying the maximum and minimum quantities that can be retained on screens of various sizes of mesh. The grading of aggregate is so important that, when natural grading of an aggregate does not fall within specification limits, screening into size fractions and recombining to produce a satisfactory grading are justified.

Surface Texture

The roughness and pore characteristics of the surface and near-surface portions of aggregate particles create a surface texture which in large part determines the integrity of the bond established between the particle and the cement paste. The surface texture reflects the original internal structure and composition of the particles as well as the natural and artificial processes of impact and abrasion to which they have been subjected.

Specific Gravity

Specific gravity of aggregate influences the unit weight of concrete but is of direct importance only where design or structural considerations require that concrete have an unusually high or low unit weight. Although low specific gravity of an aggregate is frequently considered an indication of unsoundness, numerous exceptions to this criterion prevent its application without confirmation by other means.

Porosity

A rock or mineral particle can be penetrated by water to the extent that interconnected voids or fractures are present. The amount of water absorbed depends on the abundance and size of the internal voids and fractures, and the rate of penetration depends on their size and continuity. Porosity, permeability, and absorption strongly influence chemical stability, abrasion resistance, elasticity, and apparent specific gravity of particles, as well as the degree of bond between particle and cement.

Volume Change

Volume change in aggregate resulting from changes in moisture content and temperature is a common source of injury to concrete. Shales, clays, and some rock materials expand by absorption of water and shrink on dehydration. In designing structural elements, allowance must be made for thermal volume changes of concrete, which are influenced by the average thermal expansivity of the aggregate. Damaging internal stresses may develop when the change in volume of an aggregate due to temperature is different from the change produced in the cement paste.

Coatings

Coatings form on the surfaces of natural aggregates through deposition of mineral substances from ground water. Coatings usually are composed of clay, silt, or calcium carbonate; but opal, iron oxides, gypsum, manganiferous substances, and soluble phosphates can occur as coatings. Particles with surface coatings are generally undesirable for use as concrete aggregates. The bond between particle and coating may be weak and thus will decrease strength of aggregate-cement bond. Many natural coatings contain substances (such as opal) susceptible to reaction with alkalies in cement. Soluble alkali salts may augment alkalies in cement; other salts may alter the course of cement hydration. In some cases, coatings may be essentially inert and strongly bonded and may actually increase strength of aggregate-cement bond.

Deleterious Impurities

Natural aggregate is commonly contaminated by dirt, silt, clay, mica, coal, humus and other organic matter, and various salts. These substances act in a variety of ways to decrease strength and durability, cause unsightly appearance, or complicate processing and mixing operations. They may increase water requirements of the concrete; they may be physically weak or susceptible to breakdown by weathering; they may be so active chemically as to inhibit normal hydration of cement or react with cement constituents. Fortunately, excesses of deleterious impurities may frequently be removed by simple treatment. Silt, clay, soluble salts, and some lightweight substances are usually removable by washing. Special processes may be necessary for less amenable substances, or their removal may not be practicable.

Mineral and Chemical Properties

The mineralogic and chemical composition and the internal texture and structure of particles control the physical and chemical properties of aggregates. Few, if any, rocks or minerals are inert when enclosed in concrete. Some may contain water-soluble constituents which can be leached, with attendant loss of strength and increase in porosity. Leached material may form unsightly efflorescence or modify normal hydration of cement. Unstable minerals are susceptible to oxidation, hydration, or carbonation and may cause concrete to become distressed. Certain minerals are capable of base-exchange action in which alkalies in the minerals are exchanged for calcium in the cement solutions; released alkalies may then attack susceptible aggregate particles. Some minerals—opal, chalcedony, tridymite, cristobalite, and heulandite, and rocks such as glassy or cryptocrystalline rhyolites, dacites, and andesites—and opaline and chalcedonic cherts and phyllites are reactive with high-alkali cements (cement containing more than 0.6 percent $Na_2O + K_2O$ expressed in equivalents of Na_2O) and can cause deterioration of concrete through production of alkalic silica gels which subsequently absorb water osmotically from the cement paste, developing hydrostatic pressures in excess of the tensile strength of concrete.

Thermal compatibility between mineral particles and cement paste significantly influences quality of cement when the linear thermal coefficient of expansion of the mineral is decidedly lower than that of the cement paste. Some difficulty is experienced with minerals that have different thermal coefficients of expansions in different crystal directions. For example, with increasing temperature calcite expands greatly in one crystallographic direction and contracts in another direction.

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Chapter 25

APPLICATION OF STUDIES OF THE COMPOSITION OF CLAYS IN THE FIELD OF CERAMICS *

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This chapter states briefly the factors of composition which determine the properties of clays and discusses the relation of the factors of composition to the particular properties of clays which determine their use for ceramic purposes. The practical application of studies of the composition of clays, particularly in the field of ceramics, is also discussed.

THE COMPOSITION OF CLAY MATERIALS

It is generally agreed by present-day students of clays that clay materials are composed essentially of crystalline particles of members of any one or more of a few groups of minerals known as the clay minerals (Grim, 1942). The clay minerals are hydrous aluminum silicates, frequently with some replacement of the aluminum by iron and magnesium and with small amounts of alkalies and alkali-earths. In some clay minerals, magnesium and iron completely replace aluminum. In addition to the clay minerals, variable amounts of quartz, limonitic material, feldspar, pyrite, organic material, and a host of other minerals may be present as extremely minor constituents, or as prominent constituents in some clays. Most of the clay minerals occur in flat, flake-shaped particles. The unit shape of some clay minerals is lath- or fiber-shaped. The clay minerals occur in most clay materials in particles less than about 0.005 millimeter in diameter. Table 1 lists the common clay mineral groups together with their composition.

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TABLE 1

COMMON CLAY MINERALS

1. Kaolinite group
   (a) Equidimensional flake-shaped units
       Kaolinite: $(OH)_8Al_4Si_4O_{10}$
   (b) Lath-shaped units
       Halloysite minerals: $(OH)_8Al_4Si_4O_{10}$
       $(OH)_8Al_4Si_4O_{10} \cdot 4H_2O$
2. Montmorillonite group
   (a) Equidimensional flake-shaped units
       Montmorillonite: $(OH)_4(Al_4 \cdot Fe_4 \cdot Mg_4)Si_8O_{20} \cdot nH_2O$
   (b) Lath- or needle-shaped units
       Nontronite: $(OH)_4(Fe_4 \cdot Mg_4 \cdot Al_4)Si_8O_{20} \cdot nH_2O$
       Hectorite: $(OH)_4(Mg \cdot Li)_6Si_8O_{20} \cdot nH_2O$
3. Illite group
   Insufficient data to subdivide: $(OH)_4K_y(Al_4 \cdot Mg_4 \cdot Fe_4)(Si_{8-y} \cdot Al_4)O_{20}$
4. Miscellaneous fiber-shaped units
   Attapulgite: $(OH_2)_4(OH)_2Mg_5Si_8O_{20} \cdot 4H_2O$
   Sepiolite-like: $(OH)_4Mg_6Si_8O_{20} \cdot ?H_2O$
5. Clay minerals resembling chlorite and vermiculite are known to occur, but insufficient data are available for their classification.

FACTORS THAT CONTROL THE PROPERTIES OF CLAYS

The factors that control the properties of clays may be listed as follows:

(1) Clay mineral composition: the kind of clay minerals, their relative abundance, and their particle-size distribution.

(2) Non-clay mineral composition: the kind of non-clay minerals, their relative abundance, and the size distribution of the particles of each mineral.

(3) Electrolyte content: the amount and kind of exchangeable bases and water-soluble salts.

(4) Organic content: the amount and kind.

(5) Miscellaneous textural characteristics such as shape of quartz grains, degree of parallel orientation of the clay mineral particles, silicification.

The clay mineral composition is usually the dominant factor controlling the properties of clays, but in some clays the other factors play a dominant role. It is particularly significant that relatively small amounts of certain components may exert a very great influence on some of the properties of a clay (Grim, 1948). As will be shown, this applies to the clay minerals, electrolyte content, organic content, and non-clay mineral content.

RELATION OF THE CERAMIC PROPERTIES OF CLAYS TO THEIR COMPOSITION

The object of the following discussion is to provide some understanding of the wide variation in the properties of clays and the causes of such variations. An understanding of the properties of clays is essential to any satisfactory evaluation of economic potentialities of a clay deposit. No attempt is made to consider the theory of such properties or the methods for their specific evaluation, since there is an abundance of information in the ceramic literature concerning these matters.

PLASTICITY

When mixed with certain moderate amounts of water, clays generally can be deformed under pressure without rupturing, and the deformed shape is retained after the pressure is removed. A clay that becomes plastic readily with a small amount of water and that deforms easily over a wide range of pressures is in general most usable.

Plasticity values for various common clay minerals are given in Tables 2 and 3. The range of plasticity values is a result of variations due to particle size, character of exchangeable base, and the like. In the case of halloysite, the high and low hydration forms have substantially no plasticity, whereas the intermediate stage has some plasticity.

Clays composed of illite and kaolinite usually have good working properties, and the plasticity tends to increase as the particle size decreases. Montmorillonite clays are frequently exceedingly plastic and require large amounts of water to develop the plastic state. Small amounts (± 5 percent) of montmorillonite in a clay material will generally provide a material with considerably higher plasticity than it would otherwise have. Similarly, small additions of montmorillonite clay greatly enhance the plasticity of a relatively non-plastic material.

A clay material that contains a considerable amount of non-clay material frequently has better working properties than a clay material composed solely of clay minerals. The application of this generality depends somewhat on the kind of clay, the type of ceramic ware to be provided, and the method of manufacture. It is most applicable to montmorillonite clays, and particularly to structural clay products. Clays containing as much as 50 percent non-clay minerals often have

TABLE 2

The Plastic and Liquid Limits and Plastic Index of Some Clay Minerals

[After White (1947)]

Clay	Particle Size	Plastic Limit [1]	Liquid Limit [1]	Plastic Index
Illite				
Grundy Co., Ill.	<1.0 micron	39.59	83.00	43.40
	<0.5 micron	52.27	103.65	51.38
LaSalle Co., Ill.	<1.0 micron	46.21	85.55	39.34
	<0.5 micron	52.98	111.25	58.27
Vermilion Co., Ill.	1.0 micron	44.44	95.05	50.61
Kaolinite				
Union Co., Ill.	Whole	36.29	58.35	22.06
	<1.0 micron	37.14	64.20	27.06
	<0.5 micron	39.29	71.60	32.31
Dry Branch, Ga.	Whole	30.0	35.0	5.0
Montmorillonite				
Belle Fourche, Wyo.	Whole	97.04	625–700	528–603
Pontotoc, Miss.	<1.0 micron	109.48	175.55	66.07
	Whole	81.41	117.48	36.07
Attapulgite				
Attapulgus, Ga.	Whole	116.64	177.80	61.16
Halloysite				
Eureka, Utah	Whole	51.81	62.30	10.49

[1] The plastic limit is the water content at which the clay can just be rolled into a thin thread. The liquid limit is the water content at which the mass just begins to flow. The water content is based on water loss at 110° C. For details of the test see Casagrande (1932).

TABLE 3

Water of Plasticity [1] for Various Clay Minerals

[After White (1947)]

Clay Minerals	Water of Plasticity
Kaolinite	8.89– 56.25
Illite	16.95– 38.5
Montmorillonite	82.9 –250.0
Halloysite	33 – 50
Attapulgite	92.6±

[1] The water of plasticity is the percent of water based on water loss at 110° C. required to develop a workable plastic state.

excellent working properties, and considerably less clay mineral may be present if the product is to be formed by dry pressing. Unsorted non-clay mineral particles provide greater density in the formed ware than particles of uniform size and are, therefore, most desirable.

Small amounts of organic material enhance the plastic properties of some clays. However, not all types of organic material increase the plasticity, and it is not possible to predict generally the influence of organic material in a particular clay. The plastic properties of a clay vary somewhat with the content and character of exchangeable bases and soluble salts. Thus, the addition of soda ash (Na_2CO_3) to a clay carrying exchangeable calcium tends to reduce the amount of water necessary to obtain a given degree of plasticity.

Suspension Characteristics

All the clay minerals form suspensions in water if their particle size is sufficiently small and if there is the proper electrolyte content. The montmorillonite minerals, attapulgite, and perhaps the sepiolite-like minerals are more easily placed in suspension than the other clay minerals, because they break down very easily in water to exceedingly small particles, because of their adsorptive power for electrolytes, and because of their influence on the state of the water immediately surrounding them (Grim, 1942).

When certain montmorillonite clays carry sodium as the exchangeable ion, their suspensions in water have a high degree of thixotropy. The thixotropic property would be detrimental in some ceramic applications, as in slip casting, and advantageous in others, as in steel enameling. Small amounts of montmorillonite in a clay or added to a clay greatly enhance suspension-forming characteristics.

Bonding Strength

As shown in Table 4, the montmorillonite clay minerals have greater bonding strength than any of the other clay minerals studied so far. Montmorillonite clay carrying calcium (Mississippi) has higher green strength than a similar clay carrying sodium (Wyoming). Sodium montmorillonite clays have the highest dry strength. Green strength refers to the strength of a compacted test piece containing tempering water. Dry strength is the strength of the compacted test piece after drying at 110° C. for 2 hours. The bonding strength of illite and kaolinite clays increases as the particle size decreases, and halloysite clays in an intermediate state of hydration have higher strength than either the high- or low-hydration form.

TABLE 4

BONDING STRENGTHS FOR CLAY MINERALS

[After Grim and Cuthbert (1945)]

	Clay	Opt. H_2O [1]	Max. GCS [2]	Opt. H_2O [1]	Max. DCS [3]
	%	%		%	
Kaolinite					
Grundy Co., Ill.	8	1.7	14.6	4.5	77
Illite					
Grundy Co., Ill.	8	1.9	12.7	4.5	90
Montmorillonite					
Belle Fourche, Wyo.	8	2.07	24.1	3+	100+
Pontotoc, Miss.	8	2.65	30.5	5	90
Halloysite					
Eureka, Utah	8	2.95	21.3	5	30

[1] Optimum H_2O content is the amount of tempering water necessary for maximum compression strength in mixtures of 8 percent clay and 92 percent standard testing sand.

[2] Green compression strength.

[3] Dry compression strength.

In ceramic processes, it is necessary to have only sufficient dry and green strength so that the ware can be handled without deformation and stacked in a kiln before firing. In general any clay material with a fair amount of clay mineral (± 50 percent) and non-clay material that is not sorted or coarser than sand will have adequate strength. Strength can be given to a clay deficient in this property by the addition of some organic binder or a strong natural clay like a montmorillonite clay (bentonite) or a ball clay. Ball clays are very fine-grained, light-burning clays that are composed largely of kaolinite but usually contain some organic material which is partly responsible for their strength.

As noted for montmorillonite, the strength of a clay may be related to its exchangeable-base and soluble-salt composition. The addition of soda ash to some clays increases their strength, particularly the dry strength.

DRYING SHRINKAGE

Economic use of a clay requires that the drying shrinkage be uniform, small in amount, and develop without cracking the formed piece.

Clays which require large amounts of water to develop the plastic state will show high drying shrinkage.

In general montmorillonite, when present in more than small amounts, increases shrinkage greatly. Clays composed of kaolinite and illite tend to have moderate drying shrinkage unless the component clay minerals are exceedingly fine-grained (minus 1 micron).

Non-clay mineral components such as quartz and feldspar reduce the drying shrinkage when they are present in a clay. Shrinkage characteristics are in general improved by the presence of moderate amounts (25 to 40 percent) of such components. It is common practice to add non-clay material to reduce the high shrinkage of some clays.

To be of commercial value a clay must form ware that will not be sensitive to considerable variation in drying conditions. The ware must not check or crack during drying, even though there is a large variation in time, temperature, or relative humidity during the drying operation. Actual tests are necessary to determine this point, but, in general, clays with very high clay mineral content (particularly if the clay mineral is very fine-grained) and montmorillonite are difficult to dry satisfactorily.

Firing Characteristics

Firing characteristics of a clay are: its shrinkage during firing; its color after burning; the temperature range during which it vitrifies; its resistance to heat or refractoriness; and the strength, texture, and other properties of the fired ware. Small quantities (a few percent) of certain components of clays, notably alkalies, alkali-earths and iron, may exert a controlling influence on the firing characteristics of a clay. The influence of certain of these minor components may depend on whether the component is present alone or mixed with some other constituent. Thus the effect of iron on color varies somewhat with the presence of lime and alkalies in a clay. Furthermore, the conditions under which a clay is fired, the rate of firing, and oxidizing or reducing conditions also influence the firing properties.

It follows from the foregoing that variations in firing characteristics are exceedingly difficult to predict, and that actual firing tests are necessary for the evaluation of the burning properties of a clay. However, a few general relationships seem to be established.

Kaolinite clays tend to be light-burning (white if pure) and refractory. The color darkens, usually to a shade of red, and the resistance to heat decreases as the kaolinite is mixed with increasing amounts of illite and montmorillonite. Obviously iron in the non-clay minerals (limonite, pyrite, etc.) will also cause a change in color, and alkalies and alkaline earths in feldspar, etc., will reduce the refractoriness.

Clays composed of a single clay mineral usually have a shorter temperature interval between the beginning of vitrification and complete fusion than clays composed of a mixture of minerals. This seems to be more applicable to illite and montmorillonite clays than to kaolinites. Factors other than mineral composition influence the vitrification range. Thus the vitrification range tends to increase as the range of particle size increases. The presence of alkali-earths frequently tends to shorten the vitrification range, and this is one reason why many calcareous clays are difficult to burn.

Similarly, clays composed of a mixture of clay minerals are apt to have lower shrinkage during burning than substantially monomineral clays. This again is more applicable to illite and montmorillonite clays than to kaolinite clays.

Certain clays tend to bloat or swell on firing when they are heated to a temperature at which considerable vitrification takes place. Illite and montmorillonite clays, particularly if they are relatively pure, have a tendency to bloat. Calcareous illite and montmorillonite clays seem to bloat very easily. A low-fusion temperature and short vitrification range are among the factors that favor bloating.

INDUSTRIAL APPLICATION OF INVESTIGATIONS OF THE COMPOSITIONS OF CLAYS

Studies of the composition of clays are of practical importance in several ways in the solution of problems involving the use of clays for ceramic and other purposes.

Evaluation of Clays for Ceramic Use in an Areal Study

Frequently there is the problem of determining if the clays in a given area are particularly suitable for any ceramic use. Obviously such a problem can be solved by making complete ceramic tests of samples of all varieties of clays. This procedure is expensive and time-consuming if there are many varieties of clays to be tested, and if the area is large. A simpler and more rapid procedure is to determine the mineralogical composition of the clays and then select (on the basis of the analytical data and the general relation between composition and properties) those clays that appear to be particularly suited for certain ceramic uses. The ceramic properties of those clays can then be determined in detail. The determination of the composition of the clays does not take the place of determinations of ceramic properties, but it presents a rapid method of eliminating the worthless materials.

Although it is beyond the scope of this paper, it should be noted that there is a correlation between the composition of clay materials and uses of clay outside the field of ceramics, for example, in drilling muds, decolorizing oils, fillers, etc. Determinations of composition, therefore, also permit the selection of promising samples for commercial use in fields other than ceramics.

EVALUATION OF A PARTICULAR CLAY DEPOSIT

A geologic study of a clay deposit involves two distinct problems: first, the determination of the geologic setting; and, second, the uniformity of the properties of the clay in the deposit. The solution of the first problem is straightforward geology; it provides data on the size of the deposit, overburden, ground-water conditions, large variations in character, etc.

The determination of uniformity of material in a clay body is apt to be difficult, but it is of great importance. The commercial utilization of a clay cannot be successful unless the deposit contains a large amount of clay of highly uniform properties or capable of simple beneficiation so that it can be made uniform. Any utilization of clay is inherently based on certain properties that the clay possesses, so that any change in the properties of the clay in a given deposit is likely to cause great difficulty in its processing or use. American producers of clay have not always realized the necessity of producing a uniform product, and only after this was accomplished were they successful in competing with clays that were imported into this country.

Clay deposits seem to be inherently variable. A casual examination may suggest that a clay body is uniform, whereas detailed tests will reveal it to be quite variable. In other words, the outward appearance of uniformity does not necessarily indicate uniformity in properties. The fact that very small variations in composition may cause large variations in properties must mean that important changes in physical properties are often not accompanied by any changes in gross characteristics. This is an exceedingly important point, and geologists and others have been led into costly blunders because they assumed that clay was inherently a relatively inert, uniform material that could be evaluated by superficial study. Nothing could be further from the truth.

The detection of variations in properties involves the study of the properties of many samples. Usually it is not enough to detect variations in properties; the cause of the variations, their relation to composition, and the occurrence of the clay in the field are also essential. It is frequently necessary to predict the occurrence of clays with particular properties in a given deposit before it can be evaluated and mined. In addition, the variable properties of a clay cannot be controlled by beneficiation, and the variable properties cannot be compensated for in processing unless the cause of the variation is known.

Evaluation of a clay deposit therefore should include a thorough study of all aspects of the occurrence, origin, and composition to reveal the causes of any variations in properties of the clay. Many examples could be given to illustrate the importance of this, but one will suffice. Certain beds of kaolin in the Georgia area contain small amounts of montmorillonite in addition to the kaolinite. The presence of montmorillonite does not change the appearance of the clay, and in fact is not revealed unless a careful analytical study is made, yet the presence of the montmorillonite changes the properties of the kaolin so that it is not usable for certain purposes. Obviously any information about the factors controlling the distribution of the montmorillonite in the kaolin is of great importance to the kaolin producers.

Search for Clay of a Particular Type

The application of studies of the composition of clays to the search for particular types of clay can best be shown by an illustration outside the field of ceramics. Some catalysts used in the making of gasoline are prepared from clays. Only a very few deposits of clay suitable for this use have been found, and each clay has a particular composition and an origin which requires a certain geologic setting. A knowledge of these factors obviously permits one to spot areas throughout the world in which such clays are most likely to occur.

Solution of Ceramic Processing Problems

A plant ceramic engineer spends considerable time studying processing problems which arise either because of variations in the processing technique or because of variations in the raw materials being used. The solution of problems of the latter type is expedited by a knowledge of the composition of the raw material being used and its relation to properties. Once the fundamental cause of the properties is known, the solution to the problem is often obvious. For example, a clay plant in a midwestern state operating on a series of glacial clays suddenly found its percentage of rejected brick to increase greatly because of lack of strength in the dried and fired brick. An examination showed the presence of a lens of silt which had gone undetected. More thorough mixing of the clay before processing to distribute the silt uniformly solved the problem.

Frequently such processing problems are far more complicated, and the cause begins to appear only after very thorough analysis of all factors of the composition of the clay.

Plant Control for Uniformity of Material

It is obvious from the foregoing discussion that both producers and users of clay are interested in clay with uniform properties. They are, therefore, interested in tests, which usually must be rapid, to detect variations in properties and, if possible, the cause of the variation in properties. Simple determinations of properties are, of course, used in plant-control work, but frequently a test to show variation in composition is more satisfactory because it shows something of the cause of the variations in properties *in addition to* the simple facts of property variation itself. Again an example will suffice to illustrate the point. Differential thermal analysis (Grim, 1942) has been found to be an excellent instrument for plant control because it provides information about several factors of the composition of a clay, so that, in addition to showing that a clay sample has varied, it reveals the nature of the variation.

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Chapter 26

FOUNDRY SANDS

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The term *foundry sand* is applied to those sands which are used for making the molds and cores in which metals are cast. The molds form the outside of the casting, and the cores make the hollows in it.

These materials are of considerable economic importance. In 1947 the tonnage produced in the United States amounted to 8,308,434 short tons valued at $11,944,228. In addition to this, some sands were imported. Michigan, New Jersey, Illinois, Ohio, and New York were the leading producers.

Foundry sands are widely distributed in the United States, but only special types of sands are suitable for this purpose, because the sands have to meet rigid requirements of permeability, strength, and volume change with temperature. For a more detailed discussion of foundry sands than given in this chapter, see Ries (1948).

The predominating mineral in most foundry sands is quartz, and next to it in abundance is feldspar. In most foundry sands the feldspar content is relatively low, particularly in sands used for casting steel. Some of the glacial outwash sands of central New York contain appreciable amounts of feldspar. The sands of the Bridgeton and Pensauken formations of New Jersey contain as much as 15 percent. In California most of the soft Eocene and Miocene sands are strongly feldspathic, as are also the dune sands on Monterey Bay, California. Sands containing as much as 30 percent feldspar have been used in Illinois.

Mica is present in small amounts in some foundry sands, but highly micaceous sands are not used. Many sands contain small amounts of dark minerals such as zircon, ilmenite, rutile, and magnetite. Some sands contain minor amounts of leucoxene, staurolite, kyanite, tourmaline, and garnet.

The most common clay mineral in foundry sand is illite, but kaolinite and montmorillonite have also been reported. Some sands are practically free from clay, and the foundryman often refers to these as sharp sands. Those sands which contain clay mixed with the sand grains are referred to as naturally bonded sands, and those free from clay, to which the latter is added before use, are called synthetic sands. Bentonite and fire clay are the materials most commonly added to form the bond. Practically all steel foundries now use synthetic sands, and their use is extending to the casting of iron and other metals.

PROPERTIES OF SAND GRAINS

Shape of sand grains. Foundry sand grains vary in shape, size, and assemblage. In shape they may be angular, subangular, or round. They may also consist of aggregates of smaller particles cemented together by silica, iron, or calcium carbonate. For illustration of the separate sizes of a number of different sands see Ries and Conant (1931, p. 353). The degree of angularity varies in different sands, but most grains are either angular or subangular. Round grains are rare and occur usually only in sizes larger than 40 mesh (0.4 millimeter).

Most sand grains contain minute fractures, which may cause the grains to crack on heating, thus developing fines when the sand is exposed in the mold to the heat of the molten metal. The foundryman often refers to these cracks as cleavage.

The surface of sand grains may be either smooth or rough, and the smooth surfaces are sometimes frosted. In addition, the surface may be clean, or it may be coated with a film of foreign matter such as clay or iron oxide. It is probable that rough or coated surfaces offer a better attachment for the bond.

Fineness of sands. The size distribution of the grains affects the type of casting for which the sands are used. In making a fineness test to determine the percentage of different grain sizes, a sample of 50 grams of dried sand is usually taken. Clay if present is first separated by stirring the sand in a special jar in water containing sodium hydroxide.

The suspension is then allowed to stand, the grains larger than 20 microns settling in 5 minutes. The material still in suspension is removed by decantation, the settled material stirred again, and the process repeated until the supernatant liquid is clear. The grains up to 20 microns are known as AFS clay, which includes both true clay and fine silt.

The settled material in the jar is then removed, dried, and screened, usually with sieves of the U. S. Bureau of Standard Series, but sometimes with the W. S. Tyler sieves.

Grain-fineness number. After a sieve test is made, it is customary to calculate the average fineness, which represents the size of grain that would be formed if all the material were formed of grains of uniform size. The method consists in multiplying the sand percent retained on each sieve by a certain factor. The sum of these products is divided by the sum of the grains, and the quotient represents the average fineness. The chief disadvantage of the grain-fineness number is that two sands may differ in grain-size distribution and thus differ in physical properties for foundry purposes, yet have the same fineness number. A better idea of the distribution may be gained by expressing the fineness graphically by means of the grading-size curve (weight-accumulation curve) or the size-frequency curve (histogram). The grading-size or cumulative curve is an S-shaped curve which presents percentage of particles passing given sieve sizes. The size-frequency curve is a peak-shaped curve similar to the probability curve.

The advantages of the cumulative curve over the size-frequency curve are: (1) it gives a smooth curve; (2) sieves that retain little material can be eliminated or other sizes added without distorting the curve; (3) faulty sieves are indicated by a break in the curve when different samples are sieved; (4) it is more practicable for specifying types of sands required because it permits the specification limits to be plotted as two curves rather than as points falling between two limiting curves already plotted; and (5) the data for silt- and clay-size particles obtained with the hydrometer can be plotted on the same graph, as a continuation of the line presenting the sieve data.

PROPERTIES OF FOUNDRY SANDS

Sands used for molds and cores must possess certain properties, and unless these are developed to the right degree the sand is useless for foundry purposes. This fact is not always realized by those not familiar with the subject. The properties which the sands must possess are:

(1) Sufficient cohesiveness to hold together when moist, and this necessitates the presence of some bonding material. (Clay is the common natural bond and is present in the naturally bonded sands. If the sand has no clay bond, it must be mixed with clay or some artificial binder in the proper amounts. The types of clay commonly used are

fire clay, bentonite, and illite. Various oils and organic substances are also used. The sand mixture must have sufficient moisture added to it to cause the particles to cohere.)

(2) Sufficient refractoriness to resist the heat of the molten metal.

(3) Sufficient strength to resist the pressure of the metal.

(4) Sufficient permeability to permit water vapor and gases to escape outward from the mold instead of being forced into the molten metal.

(5) Proper texture so that the mold surface will be sufficiently smooth to produce a smooth surface on the casting and not develop surface defects.

These are the main requisites, and the proper mixture is obtained by using sand of appropriate grain size, proper amount of bond, and correct amount of moisture. The various properties which control the conditions above mentioned can be determined by special tests, most of which have been standardized by the American Foundrymen's Society (formerly the American Foundrymen's Association). A number of these tests are made on the sand at room temperature; others are performed on the material at elevated temperatures. After a sand mixture of the desired properties is found, an effort is made to keep these properties fairly constant. The properties are briefly described below.

Permeability. The sand must be sufficiently permeable to allow volatile matter to pass through it as the casting cools. Permeability should not be confused with porosity, as it often is. Permeability is an important property, because the hot metal in contact with the sand generates a mixture of water vapor and gases from organic compounds. These gases must be able to pass outward through the sand; otherwise they may be forced into the molten metal and cause defects.

Fine-grained sand, other things being equal, has less permeability than coarse-grained sand. The quantity and character of the clay also exert an effect, as does the amount of moisture. The permeability increases with the amount of moisture up to what is known as the optimum, after which it decreases.

Permeability is determined by measuring the rate at which air flows through a standard AFS specimen under standard pressure. This standard specimen is 2 inches in diameter, 2 inches high, and is compacted or rammed under standard conditions (American Foundrymen's Association, 1944).

The permeability of a sand is determined under several conditions: (1) *base permeability,* or permeability of the packed, dry sand grains with no clay or other bonding substance; (2) *green permeability,* or permeability of a molded mass of sand in a moist condition; (3) *dry permeability,* or permeability of a molded mass of sand which has been dried at 105° to 110° C. and cooled in a desiccator to room temperature; (4) *baked permeability,* or permeability of a molded mass of sand baked at a temperature above 100° C.

Green compressive strength. To be effective foundry sands must possess adequate strength. In order to test the strength, the green compressive strength is determined immediately after the sand has been mixed. For details of this test see American Foundrymen's Association (1944). The green compressive strength generally increases with the amount of clay bond, but different clays have different effects. The compressive strength increases with the addition of moisture to an optimum condition and then decreases with the addition of more water. According to Grim and Cuthbert (1945) the strength increases from 12 pounds per square inch for a moisture content of 1.0 percent to 18 pounds per square inch for a moisture content of 2.0 percent and then decreases to 9 pounds per square inch for a moisture content of 4.0 percent. The strength also increases with amount of tamping or ramming during preparation of the sample. Work by Davies and Rees (1944) on synthetic sands suggests that round grains give the sand greater strength than angular grains.

Dry compressive strength. Sands change in strength as they dry. A measure of strength called the dry compressive strength is taken after the sand has dried for 2 hours at a temperature of not less than 105° C. The dry compressive strength varies with (1) amount of moisture in the green sand, (2) extent of mixing, (3) number of rams, (4) content of clay, water, or other bonding material, and (5) grain size.

Flowability. The American Foundrymen's Society defines flowability as "the property of a foundry sand mixture which enables it to fill pattern recesses and move in any direction against pattern surfaces under pressure." It is, as can be readily understood, an important property, but as yet there is no standard test for it, although several have been suggested (Chadwick, 1940; Kyle, 1940; Lissell and Ash, 1942).

Air set strength. Another property is the air set strength, which is the strength the sand develops when it is allowed to stand in the air, even though all its moisture has not evaporated (Grim and Cuthbert, 1945).

Deformation. The deformation is defined as the change in linear dimensions of a sand mixture in response to stress. It is a measure of the brittleness of a sand mixture. The deformation is expressed in thousandths of an inch per inch. By taking the product of deformation and green compressive strength and multiplying this by 1,000, the STN, or *sand toughness number,* which is an indication of the workability of the sand, is obtained. By properly controlling the deformation, the foundryman may avoid various troubles and even casting defects.

EFFECT OF ELEVATED TEMPERATURE

Foundry sands react to different metals in different ways at elevated temperatures. A number of procedures have been used to test the sand under these conditions, although no tests have yet been standardized.

Hot compression test. A specimen of the sand $1\frac{1}{8}$ by 2 inches is placed in a special furnace and heated to various temperatures; then it is subjected to increasing pressure until it collapses. Some clay bonds, as, for example, bentonite, give a higher hot strength than fire clay. The hot compressive strength also tends to increase as the temperature rises to 1,800° or 2,000° F., after which it decreases. No strict rules can be laid down for the hot compression test, and it is necessary for the foundryman to determine what hot strength gives the best results with a particular casting, and adjust the mixture accordingly.

Expansion and contraction. Sand grains expand when heated, whereas clay contracts. If a bonded sand is heated, it expands at first, but, with continued rise in temperature, it begins to contract. If this expansion of the sand in the mold is too great, it causes defects in the casting. Excessive expansion is undesirable, and various means may be taken to reduce it (Dietert *et al.,* 1939; Dunbeck, 1946).

Core collapsibility. The shrinkage of solidifying metal around a core applies to it pressure which, if resisted by the core, develops tears or strains in the casting. It is therefore necessary to select a core mixture which, when hot, yields to the metal or collapses. This mixture is selected by placing a test specimen in the furnace and subjecting it to a predetermined load, often 50 pounds, and noting the time that the core can withstand this without collapsing.

Heat shock. If a test piece, when placed in a hot furnace at the casting temperature of the metal with which it is to be used, spalls or cracks, the foundryman may feel that the sand will not work well for large castings. Consequently samples are sometimes tested for heat shock.

Durability. A sand mixture may deteriorate and lose its bond strength as a result of dehydration or vitrification of the clay bond, so that the same mixture cannot be used again. This vitrification of the clay may cause agglomeration of the sand particles. Some sands may deteriorate more rapidly than others. To keep the sand up to its original strength more bond may have to be added. Naturally bonded sands have a lower durability than synthetic sands (Covan, 1942).

DISTRIBUTION OF FOUNDRY SANDS IN THE UNITED STATES

Foundry sands are widely distributed in the United States and are worked at a number of localities. Most deposits are Pleistocene or Recent in age. All types of sediments—marine, lacustrine, fluviatile, glacial, and eolian, if they have suitable properties, are used. In general there are two types of deposits: (1) siliceous sands free or nearly free from clay, and (2) naturally bonded sands.

Those of the first group vary in age from Cambrian to Quaternary and may be consolidated or unconsolidated. They require crushing as well as screening and perhaps even washing after quarrying, whereas those of the second group may need similar treatment after digging.

The consolidated sands occur in a number of states. They include the Cambrian and Oriskany sandstones of Pennsylvania and Carboniferous sandstones of Ohio; the St. Peters sandstone of Minnesota, Wisconsin, and Missouri, and the Ottawa sand of the Illinois district. The last named is especially important, and the product of this district is shipped as far as California and the Northwest. A Cambrian sandstone is also quarried at Portage, Wisconsin, and used for foundry sand.

In the Las Vegas district of Nevada are extensive deposits of Jurassic sandstone which is shipped to California in large amounts because that state is deficient in high-silica sandstone. The material has to be crushed, screened, and, in some cases, washed before shipment.

In California are extensive deposits of siliceous sandstone which for the most part are moderately soft. They are chiefly marine deposits of Eocene age, but many of them are feldspathic in character and do not always run high enough in silica to be useful in steel foundries. In Alabama, Carboniferous sandstone (Hartselle formation) has been quarried for foundry use. Other sands have been quarried in Arizona. Unconsolidated siliceous deposits are worked in New Jersey, where most of the material comes from the Cohansey (Tertiary) formation.

Some of it, however, is from the Raritan (Cretaceous) and the Quaternary deposits.

Dune sands are used in large amounts. In Michigan the production in 1947 was 1,900,000 tons. Dune and beach sand are also worked in Massachusetts, New York, New Jersey, Illinois, California, Ohio, and some other states.

The naturally bonded sands are worked in many states and are mostly of Pleistocene or Recent age. In those in the glaciated area, the molding sand deposits are usually found with glacial deposits. Recent lacustrine deposits occur in many states. As a rule, neither of these two groups of deposits is of great extent or thickness.

Marine deposits of naturally bonded sands are not extensively worked. They occur in the Cohansey (Tertiary) of New Jersey, the Pliocene of California, and the Tuscaloosa of Alabama.

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Part 5

ECONOMIC MINERAL DEPOSITS

Chapter 27

THE FIELD OF ECONOMIC GEOLOGY OF SEDIMENTARY MINERAL DEPOSITS *

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Minerals and rocks mined from syngenetic sedimentary deposits make up about 36 percent of the value of the total annual domestic mineral production (Table 1). About 3 percent of the annual output comes from altered sedimentary rocks, such as the Lake Superior iron ores, which, though their value arises from secondary enrichment, resemble sedimentary rocks more than they do rocks of any other kind. Only about 13 percent of the production comes from igneous, metamorphic, vein, and replacement deposits. The remaining 48 percent of the production consists of fluids, such as petroleum and brines, most of which are recovered from sedimentary rocks.

Notwithstanding the economic importance of sedimentary mineral deposits, it is safe to say that the principles of sedimentation, or of geological science in general, are rarely applied to their exploration and exploitation.† Most sedimentary materials have a low unit value compared to those of other origin, and many of them are relatively easy to find, appraise, and follow in mining (McKinstry, 1948, p. xv). Most companies that mine only unaltered sedimentary deposits do not employ geologists, and, if a geologist is consulted at all, usually it is to pass judgment on a property that the company is considering buying, or to solve specific problems connected with appraising the reserves or following the ore in an active mine. The principles of structural geology and stratigraphy are generally more useful in the solution of these problems than are those of sedimentation, and the mining geologist with a good background in general geology is apt to be better qualified to solve them than one who, though he has specialized in sedimentation, is not familiar with the methods of field and economic

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† If petroleum were considered a sedimentary mineral deposit, it would be a notable exception.

TABLE 1

VALUE OF 1946 DOMESTIC MINERAL PRODUCTION CLASSIFIED BY ROCK TYPE [1]

	Value	Percent of Total
Igneous rocks (including granite, basalt, pegmatite minerals, chromite, etc.)	$ 57,800,000	1
Sedimentary rocks (see Table 2)......................	2,690,000,000	36
Metamorphic rocks (including slate, marble, quartzite, anthracite coal, garnet, etc.)......................	447,000,000	6
Veins, disseminations, and replacement bodies (including salt-dome sulphur and salt, most contact-metamorphic deposits, sandstone vanadium and uranium ores, asphalt, gilsonite, and related bitumens, as well as the bulk of the metalliferous deposits)............	493,000,000	6
Residuum (including kaolin and bauxite, Lake Superior iron ores and manganiferous iron ores, most domestic manganese ores, many barite deposits, mineral pigments, Tennessee and Florida hardrock phosphate deposits, etc.)..................................	218,000,000	3
Fluids (including petroleum, natural gas, sea water, brines, etc.; surface and ground water are not included, but only because their value is unknown).....	3,590,000,000	48
Total....................................	$7,500,000,000	100

[1] Although the rocks of the earth's crust are customarily divided into three main classes—igneous, sedimentary, and metamorphic—it has long been recognized that many earth materials, such as residual and supergene ores, talus, landslides, veins, and water, are not so classifiable (see Ashley *et al.*, p. 428). Although the volume of most of these materials (water is a prominent exception) is much less than that of the three principal rock types, they are of equal, if not greater, importance economically and deserve recognition as separate rock types in any scheme of classification of mineral deposits. The additional rock classes presented in this table are provisional. Admittedly they all are not sharply definable (this characteristic they share with the traditional classes, however), and, whereas the traditional classes are defined genetically, two of the classes used here (veins, etc., and fluids) are defined descriptively. The only defense and recommendation offered for this classification is that it does allow a more simple and yet geologically significant classification of minerals (used in the broad sense, as "mineral production" or "mineral resources") actually produced than any other classification known to me.

The values for the individual minerals and rocks are not strictly comparable or accurate. As explained in the Statistical Summary of Mineral Production in the U. S. Bureau of Mines *Minerals Yearbook*, from which the data have been compiled, some production figures represent the value of the crude materials; some are reported only for refined materials; and some are reported only for the finished product (such as cement). In this compilation, the production figures totaled are of the crude material or the crudest form of the product for which figures are available. As many minerals are mined from more than one class of rock, it is difficult to tell from the general production figures available how much of the production of a given mineral comes from rocks of one class and how much from another. In addition, the uncertain origin of many minerals makes their classification difficult. Many of the errors introduced by these uncertainties should be compensating, however, and the totals are probably valid as to order of magnitude. D. F. Davidson assisted in tabulation of the data.

geology. Nevertheless there are mining problems to which knowledge of sedimentation can be applied to good advantage.

Although it would be possible to describe some principles of sedimentation that might be applied to the exploitation of sedimentary deposits, such a description is not permitted by the space available here, nor is it in keeping with the purpose of this symposium. Instead, the principal purpose of this chapter is to acquaint students of sedimentation, as well as workers in related fields of geology and engineering, with the nature and breadth of the field—the variety of sedimentary minerals and rocks currently mined, the general problems encountered, and the methods commonly used to solve them.

SEDIMENTARY ROCKS AND MINERALS CURRENTLY CONSIDERED VALUABLE

The sedimentary minerals and rocks currently considered valuable are listed in Table 2, which shows the dollar value of their domestic production in 1946.* A study of this list shows (1) that the number of minerals and rocks currently mined is large; (2) that they are diverse in chemical, mineralogical, and physical characteristics and occur in every major class of sedimentary rocks—in fact, virtually every type of sedimentary rock or mineral, in some degree of purity or physical state, is utilized for some purpose; and (3) that most of the minerals and rocks currently mined are non-metallics, most of which are valued for their content of a chemical compound, like sodium chloride or calcium carbonate, rather than of a single element, or for their physical properties, such as hardness, plasticity, grain size, state of aggregation, or color. Most of the non-metallics have a low unit value. To be commercially competitive, therefore, deposits of most of the minerals and rocks must be of exceptional purity or quality, must be close to tidewater or market, or be so situated or constituted that they can be mined or refined at very low cost.

PROBLEMS ENCOUNTERED IN THE PRODUCTION OF MINERALS FROM SEDIMENTARY DEPOSITS

Basically the problems involved in the production of minerals or rocks from sedimentary deposits do not differ from those connected

* Sedimentary deposits which owe their value to leaching, enrichment, or other types of redistribution of primary constituents, are excluded from the tabulation. Examples of deposits excluded are the Lake Superior iron ores, the Colorado-Utah vanadium ores, and the Tennessee phosphates.

TABLE 2

VALUE OF 1946 DOMESTIC PRODUCTION OF MINERALS FROM SEDIMENTARY DEPOSITS

All minerals listed below have been produced from sedimentary deposits. Some, as shown, were not produced domestically in 1946, and a few have never been mined in this country (an important amount of the foreign production is derived from sedimentary deposits—for example, columbium and tin concentrates, gem stones, monzonite, and manganese). The production figures for individual minerals are rounded off to the nearest $1,000, and no more than three significant figures are given. The value of the production of placer tungsten, ilmenite, rutile, zircon, sharpening stones, vanadium (produced as a by-product from phosphate rock), and potash salts are confidential and cannot be released separately. A. F. Mathews of the Bureau of Mines, who cooperated in many ways in the preparation of this table, has furnished a figure for the total value of these minerals, which is included in the total. John Crawford, D. F. Davidson, and Robert Boardman of the U. S. Geological Survey assisted in the tabulation and checking of the data.

Explanation of Symbols

? Small part of production may have come from non-sedimentary rocks.
?? Part of production known to have come from non-sedimentary rocks; value estimated.
??? No production figures available; value estimated.
X Confidential; value included in grand total.

I. Detrital deposits	
A. Placer concentrates	
1. Metals	
Chromite	None
Columbium and tantalum concentrates	None
Copper (chalcocite, native copper, etc.)	None
Gold	$ 20,700,000
Lead (galena)	None
Magnetite	None
Mercury	2,000 ??
Platinum metals (refined)	
Platinum	1,270,000 ?
Palladium	4,000 ?
Iridium	300,000 ?
Osmium	45,000 ?
Rhodium	78,000 ?
Ruthenium	5,000 ?
Silver	63,000
Tin	None
Titanium concentrates	
Ilmenite	X
Rutile	X
Tungsten concentrates (scheelite, wolframite, hubnerite)	X
Total value of metals produced from placers	$ 22,500,000

TABLE 2 (*Continued*)

I A. *Continued*

2. Non-metals		
Corundum		None
Emery		None
Garnet	$	75,000 ???
Gem stones		250,000 ??
Agate		???
Amber		None
Beryl (including morganite and aquamarine)		None
Chrysoberyl (including cat's eye and alexandrite)		None
Diamond		None
Emerald		None
Garnet		None
Jade		???
Opal		???
Ruby		None
Sapphire		None
Spinel		None
Spodumene		None
Topaz		None
Tourmaline		None
Quartz		None
Zircon		None
Monazite		None
Zircon		X
Total value of non-metals produced from placers	$	325,000
B. Gravel and conglomerate		
Building gravel	$	34,400,000
Grinding pebbles		60,000 ??
Millstones		10,000 ??
Paving gravel		54,300,000
Railroad ballast		6,340,000
Miscellaneous		1,440,000
Total value of production of gravel and conglomerate	$	96,600,000
C. Quartz sand and sandstone		
Sand		
Building sand	$	32,000,000
Engine sand		1,920,000
Filter sand		285,000
Fire or furnace sand		334,000
Glass sand		9,540,000
Grinding and polishing and sand-blast sand		1,380,000
Molding sand		9,530,000
Paving sand		18,000,000
Railroad ballast		262,000
Others		1,750,000

TABLE 2 (*Continued*)

I C. *Continued*

Sandstone		
Building stone	$	1,780,000
Curbing		86,000
Flagging		463,000
Grindstones		501,000
Millstones		None
Pulpstones		4,000
Sharpening stones		X
Ground sand and sandstone		
Abrasive		629,000
Enamel		168,000
Filler		205,000
Foundry		514,000
Glass		365,000
Pottery, porcelain, and tile		1,710,000
Miscellaneous		540,000
Crushed and broken sandstone		
Concrete and road metal		1,830,000
Railroad ballast		315,000
Refractory stone (ganister)		2,950,000
Riprap		654,000
Miscellaneous (including sandstone for concrete blocks, filter stone, poultry grit, rock wool, roofing granules, spalls, stone sand, chemical use, etc.)		3,330,000
Total value of production of quartz sand and sandstone	$	91,000,000
D. Clay and shale		
Ball clay	$	2,400,000
Kaolin		12,000,000 ??
Fire clay (including stoneware clay)		15,800,000 ??
Bentonite		4,360,000
Fuller's earth		3,700,000
Miscellaneous clays (including slip clay and shale)		10,000,000
Bauxite		6,000,000 ??
Total value of clay and shale	$	54,300,000
E. Miscellaneous		
Pumicite	$	820,000 ??
Total value of production of miscellaneous detrital sediments	$	820,000

TABLE 2 (*Continued*)

II. Chemical deposits	
A. Deposits formed by interaction of solutions (organic or inorganic processes)	
Calcareous marl	$ 248,000
Dolomite	
Basic magnesium carbonate	465,000
Dead burned (dolomitic lime)	10,400,000
Refractory uses	1,150,000
Limestone	
Agricultural	32,500,000
Building stone	5,840,000
Flagging	44,000
Riprap	2,050,000
Fluxing stone	20,800,000
Concrete and road metal	66,300,000
Railroad ballast	6,080,000
Miscellaneous (including crushed limestone used for alkali works, fillers, glass, whiting, mineral food, etc.)	22,100,000
Lime, quick and hydrated	40,600,000
Oyster shells	357,000
Iron ore (includes non-residual Clinton ores only)	15,600,000
Magnesite	None
Manganese ore	None
Phosphate rock_	23,300,000
Pyrite (coal brasses)	5,000 ???
Sulphur	None
Uranium	None
Vanadium	X
Copper	None
Silver	None
Diatomite	3,300,000
Barite	None
Glauconite	425,000
Coal (bituminous and lignite)	1,810,000,000
Peat	1,010,000
Total value of production from deposits formed by interaction of solutions	$2,060,000,000
B. Deposits formed by evaporation of solvents	
Borates (chiefly borax, kernite, colemanite, ulexite, priceite)	$ 9,580,000
Gypsum and anhydrite	12,400,000
Salt	13,300,000 ??
Potash salts	X
Strontium minerals (celestite)	4,000

TABLE 2 (*Continued*)

II B. *Continued*		
Magnesia-caustic calcined, and refractory	$	1,000,000 ??
Sodium carbonate (trona, gaylussite, etc)		1,000,000 ??
Sodium sulphate (mirabilite, thenardite, etc.)		500,000 ??
Total value of production of substances formed by evaporation of solvents	$	37,800,000
III. Detrital-chemical sediments		
Cement, portland (includes cement rock, marl, oyster shells, limestone, clay and shale, blast furnace slag gypsum, sand and sandstone, iron, and miscellaneous materials)	$	292,000,000
Cement, natural and pozzolan		4,160,000
Rottenstone		16,000
Woolrock (included in values for stone)		
Total value of production from detrital-chemical sediments	$	296,000,000
GRAND TOTAL (value of production from all types of sedimentary deposits)	$	2,690,000,000

with deposits of any other origin, and they are associated with the following steps in the production of the mineral or rock: (1) finding the deposit; (2) appraising it; (3) extracting the rock or mineral from the ground; and (4) treating it prior to or during the manufacture of the finished product. These steps are not always clearly defined or inseparable, and not all are involved in the production of minerals from many deposits.

THE SEARCH FOR SEDIMENTARY DEPOSITS

The realization that mineral deposits are small in volume and that exploration and mining are expensive has a sobering effect on geologists who, until faced with the actual problem of finding a deposit, think they understand something of the origin and distribution of mineral deposits. Depending on the location, quality, and minability, deposits of manganese, potash, phosphate, and gravel need comprise only about 10,000, 40,000, 125,000, and 500,000 cubic feet, respectively, to be of value to small producers. Geologically speaking, even "large" deposits are apt to be very small. Even the most modest exploration programs commonly cost several thousand dollars, and many larger programs cost several hundred thousand dollars or more. The combination of the small size of the deposit sought and the high cost of exploration requires an exacting prediction, which is admittedly beyond most geological theory. Inadequate as existing theory may be in pinpoint prediction, however, it forms the best guide available in the search for mineral deposits. But its application often requires more courage than can be mustered, and even a geologist sometimes organizes the search on a "gold is where you find it" basis.

The exploration for mineral deposits is of two general types: (1) searching for new deposits or new districts, and (2) searching for extensions of known deposits or for additional deposits in a going mine or district.

THE SEARCH FOR NEW DEPOSITS

In the past, the search for new metalliferous deposits and for deposits of many of the more valuable non-metals has been conducted almost exclusively by prospectors. In fact, most of the deposits currently mined were discovered by prospectors or are extensions of mines or prospects discovered by them. The prospector's theories may not have been valid, but their methods were exemplary, at least in their thoroughness. They covered the ground in great detail, tested any specimen that looked unusual, and, especially important, confidently dug test pits, sank shafts, or drove tunnels to explore the slightest "showing." Risk capital, in the form of time and back-breaking labor, they possessed and used more fearlessly than do mineral investors of the type ordinarily recognized.

Although the prospector has all but disappeared from this country, his discoveries are still the chief leads followed in the search for new deposits. The common practice in seeking a new property is to compile, through a study of the literature or through contacts with various individuals or associations, a list of the localities where the mineral in question has been reported, and then examine those properties or, at least, such of them as appear promising. In other words, the search for new deposits usually begins with examination of a known deposit, which probably has been examined superficially at least by a score of other geologists and engineers. Geological principles are thus infrequently applied, even now, to the search for new deposits.

The search for the less valuable non-metallics, such as construction and fluxing materials, constitutes perhaps the most notable exception to the above statements, possibly because those materials are about the only ones which, because of their extremely low unit value and the critical importance of their location with respect to construction or plant sites, did not attract the interest of the prospector. Regardless of the reason, it is true that the present search for them is demanding and receiving geologic guidance. Many state highway departments, the Corps of Engineers, the Bureau of Reclamation, railroad companies, smelter companies, and similar organizations are employing geologists to aid in the location of suitable materials. Some of the methods used in this search are discussed in other chapters in this volume and need not be recounted here. Suffice it to say that the results of application of geology to the search for many non-metallics has often led to a considerable saving in the cost of materials, not only through the discovery of materials that meet the required specifications more satisfactorily than those previously used, but also especially in locating deposits close to the project.

THE SEARCH FOR EXTENSIONS OF KNOWN DEPOSITS

Most exploration for minerals now consists in seeking extensions of known deposits or seeking new deposits in known districts. There are three good reasons for this: (1) geological theory is not sufficiently advanced to support a search for a mineral in districts not already known to contain it; (2) the presence of known mineral deposits suggests the proximity of others as yet undiscovered (look for bears where bears are known to be!); and (3) it is much more profitable to mine a material in the vicinity of a going operation (where permanent mine and mill installations have already been amortized, and where transportation and power facilities are available) than to begin mining in a new district.

As the mode of occurrence of many sedimentary deposits is simple, the search for extensions of known deposits can be guided by elementary geological theory. Many of the deposits (such as some coal, potash, phosphate, limestone, and iron formation) were deposited as blankets over areas of several hundred to several hundred thousand square miles. As these materials occur at more or less definite horizons, they can be traced without difficulty by the common stratigraphic methods. In regions of intense folding or faulting, geologic mapping is, of course, required to determine their location. Often many complex structural and stratigraphic problems must be solved in the preparation of such a map, but no geological theory is required to find the position of the mineral deposit in question once the map is available. Positive proof is required, of course, to show that the formation contains the mineral deposit; such proof may require drilling, trenching, or other types of physical exploration.

The irregular or lenticular nature of some sedimentary deposits makes the search for them much more difficult. Many of these deposits occur at one or more definite stratigraphic horizons, and this facilitates the search for them to some extent (examples include phosphate deposits of the type present in the Pliocene Bone Valley formation in Florida, and manganese deposits such as those in the Pliocene (?) Muddy Creek formation in the Lake Mead region and in the Jurassic (?) Franciscan formation in California). Exploration for these deposits begins with the preparation of a geologic map. Additional deposits may be discovered in the course of mapping simply by careful examination of available exposures and float. The same result is sometimes achieved without mapping if the geologist disciplines himself to study the ground with the same thoroughness as when he maps it (provided, of course, that the structure is simple enough that he can trace the favorable horizons without having to solve complex structural problems). If mapping or ground search does not directly provide the desired results, the favorable horizons are tested at depth by drilling or other means of physical exploration. In most places, such drilling is done on a grid—a sound plan to follow where the factors controlling the distribution of the deposit are not known. In these circumstances, the geologist pays his way by providing the engineer with information on the structure and lithology so that the favorable horizons may be tested at the lowest possible cost. From a knowledge of the habit and shape of the deposits elsewhere in the district, he may be able to help the engineer "drill out" any deposits discovered, and, of course, the geologist is chiefly responsible for the interpretation of the results obtained.

Other sedimentary deposits of irregular distribution occur in surficial materials whose distribution is related to the physiography. Examples include both ancient and modern beach and alluvial placers, peat deposits, salines in the playas of the Southwest, clays of glacial origin, and, of course, most sand and gravel deposits. These deposits are extremely important economically, not only because many of the materials have a relatively high unit value (such as the placers and salines) but also because many such deposits are amenable to mining at an extremely low cost.

The search for surficial deposits is so simplified by their relation to the physiography that prospecting is often done without the aid of a map. Use of a topographic and geologic map, however, may make the difference between a successful, inexpensive search and an unsuccessful, expensive one. This is especially true if the map shows the areal distribution of various types of surficial deposits (kames, eskers, glacial outwash, flood plain, terraces, etc.) as well as local variations in their composition and texture. Knowledge of the location of the lodes from which placers have been derived is also important in prospecting for many alluvial placers (many lodes have been discovered, incidentally, by tracing placer minerals to their sources, and, conversely, many placers have been discovered after the lode).

Geologic guidance in the search for placers and similar deposits has gone far beyond the mere location of the favorable host material, and many other geologic principles have been successfully applied. For example, the relation between the size and density of materials and the stream velocity has been used to predict the location of placer concentrations with respect to changes in gradient, channel configuration, bars, tributaries, etc. Shingling and pebble orientation have been used to determine direction of flow of streams in which now-buried placers ("drift" placers) were deposited. The pattern of ancient drainage (the products of which are now buried under lava flows, later alluvium, etc.) has been worked out locally by reconstructing the old surface from a combination of sedimentologic, physiographic, and other geologic data (including the structural pattern as well as the distribution of the bedrock formations), and a knowledge of the general structural and physiographic history has often been applied successfully to the search for concealed deposits. See Jenkins (1946) for a good summary of the geologic principles utilized in the search for placers.

APPRAISAL

The methods used in appraising deposits are considerably more advanced than those used in finding them. This is understandable for, whereas most deposits have been found at little cash outlay (even though at great cost in terms of prospector man-hours), they cannot be mined without investment of considerable capital. Investors cannot afford to develop a mine, build a mill or plant, and perhaps construct an access road or railroad spur without advance assurance that the deposit contains sufficient minable material to amortize their capital investment.

Several factors receive prime consideration in the appraisal of a mineral deposit of any kind, regardless of its genesis. The first is location of the deposit, not only with respect to railhead and access roads, but also with respect to the market. (This is especially true with many of the low-value non-metallic materials. For example, a gravel deposit more than a few miles from the highway or dam in which the gravel is to be used has no value whatsoever; a brick manufacturer distributing his products over a geographically restricted area has no interest at all in the clay deposits in another state.) The second factor includes reserves and quality of the material. The third factor concerns minability of the deposit—thickness of the bed, simplicity of the structure, nature of the walls, thickness and nature of the overburden, and similar factors that control the ease and cost of mining. The fourth factor involves the metallurgical characteristics of the material, its amenability to low-cost methods of concentration or processing, or its suitability for the purpose intended. The fifth is the availability of water, timber, fuel, power, or other raw materials that may be vital to the operation planned. The relative importance of these factors differs with respect to various materials or situations, and an unfavorable report on any one of them may be enough to eliminate the deposit from further consideration.

Many of these factors are plainly not geologic, and, actually, many examinations or appraisals are made by mining engineers or even metallurgists. Though the geologist, engineer, or metallurgist may be called on to make the complete appraisal, none is qualified to do so alone unless the property is an extremely simple one whose merits and suitability are obvious, or unless the individual chosen is a man of exceptionally broad experience and sound judgment. As a matter of fact, specialists from all these fields often share the responsibility for the appraisal of properties calling for a large capital investment.

The geologist is best qualified to determine the tonnages of various classes of materials, the position and structure of the bed, and the depth of overburden. Decisions as to what portions of the deposit are of suitable structure to be mined or milled require a thorough knowledge of mining and metallurgical methods. These decisions must be made before the tonnage of material which can be extracted at a profit can be calculated; if the geologist calculates minable reserves singlehandedly (this practice is undesirable), he at least informs himself about the requirements imposed by the mining and metallurgical methods to be employed. The discussion here deals only with calculation of tonnages of various classes of materials, not minable reserves.

The first step in estimating tonnages and in working out the position and structure of the deposit is to make a geologic map of the area. Techniques employed in mapping, choice of scale to be used, etc., are discussed elsewhere and need not be repeated here. Suffice it to say that the map must show both facts and inferences. The geologist not only needs to keep the facts separate from his conclusions for his own benefit, but others are also entitled to know the basis for his conclusions; on the other hand, the facts are seldom complete enough to show the structure and extent of the deposit, yet assumptions regarding the structure and extent are required before tonnages can be estimated or before further exploration can be conducted. Therefore, it is the task of the geologist who compiles the facts to make the first guess as to their meaning.

Unless the geologic map condemns the property, information must be acquired about the quality and thickness of the deposit. The number of intersections required to establish grade and thickness varies considerably. Blanket deposits of the type already referred to are remarkably uniform in grade and thickness over large areas, and their quality in the mining unit under consideration often can be demonstrated adequately by half a dozen samples. Other deposits may require channel sampling or drilling at intervals of a few feet or tens of feet before the quality and thickness of the material can be established. The number of samples required is one of the points that the geologist must (and is best qualified to) determine.

The prime concern in estimating tonnages of various grades of material is the physical continuity of the beds. The usual stratigraphic methods, ranging from the use of prominent marker beds to accessory minerals and fossils, are employed in tracing the beds, and the degree of success achieved often determines the reliability of the estimates.

When the deposit is demonstrated to be discontinuous or variable in grade and thickness, the accumulated measurements of thickness and quality must be interpreted. This again is the geologist's province, and, in the field of appraisal as a whole, it is the place where the principles of sedimentation are needed most. A thorough understanding of the origin of the material—its manner and environment of precipitation and deposition—are required to reconstruct the shape of the deposit, or to evaluate the importance of local variations in grade and thickness. Unfortunately such knowledge is generally lacking, and various rule-of-thumb or statistical methods must be relied on to calculate the tonnage of various classes of materials.

Even statistical methods cannot be used indiscriminately, but must be applied in the light of the best information available on the geologic nature of the deposit. If the variations in grade or thickness are of a truly random nature, certain assumptions and methods are possible that are not appropriate at all if such variations are found to have a pattern. Even though such a pattern is not understood, or is explained by incorrect theory, it is by no means ignored in the estimation of tonnages.

One of the difficult questions which frequently arises in the appraisal of mineral deposits is "What is the continuity of the ore at depth?" Here again a theory of origin is required to supplement facts, but the facts themselves can be extended considerably. When evidence to the contrary is lacking, the nature of the deposit in the area explored may be taken as a random sample of the situation that prevails at depth. If the bed in outcrops is of the same quality and thickness for miles around and, as sampled underground, shows no effects of leaching or secondary enrichment, it is reasonable to suppose that it is of the same quality and thickness wherever it is present at depth. The chief question then becomes one of structure, and the answer may require mapping of a more extended area than that in which the deposit crops out. If, on the other hand, the deposit is discontinuous where explored, it is sometimes justifiable to assume that the same quantity and quality of material is present per unit of area at depth as is present near the surface.

DEVELOPMENT AND MINING

If, on careful appraisal, the deposit appears to contain the required tonnage of minable material, steps are taken to prepare it for mining. Depending on the type of deposit, this development work may consist in detailed drilling and mapping to establish more precisely the position and attitude of that part of the deposit that is to be extracted, or it may consist only in driving haulage ways, removing overburden, and otherwise providing access to the deposit and means of removing the material from the mine once it has been loosened at the face. Mining usually begins on the first minable unit developed, and thereafter development work is carried on concurrently with mining.

Only rudimentary principles of geology were applied to the problems of mining most sedimentary deposits in the past, and these were applied by miners, shovel operators, and mining engineers who acquired their knowledge of the principles involved through actual experience with the deposit being mined. Many of the larger companies mining epigenetic deposits now employ geologists; there is a growing tendency to do the same in the mining of many syngenetic sedimentary deposits.

If a mining geologist is employed, his chief responsibility is to trace the ore, both in the development work and in mining. In many areas, exploration sufficiently detailed to form the basis for a sound appraisal of the property is by no means detailed enough to disclose all the faults and other irregularities or discontinuities in the bed to be mined; nor will all of them be found in the course of the development work. The principal means used in keeping track of the bed to be mined is detailed geologic mapping—mapping not only of the surface but also of underground workings, pit faces, and other openings. Usually a number of geologic maps at various scales are prepared and kept up to date as the work progresses. Even if systematic geologic mapping is not done, generally the location of at least the workings and mine installations are shown on some kind of map.

In some mines where much drilling or sampling is required in the course of development or mining, much of the geologist's time may be consumed in describing samples and logging core. The drudgery involved often is compensated, both to the geologist and to the company, by the results obtained in the interpretation of the data so accumulated, for no better means exists for learning the habit of the deposit than to combine mapping, sampling, and daily observation of the faces.

Another function of the mine geologist may be the periodic estimation of reserves. The reserves so estimated generally include only material blocked out and ready for mining ("measured" reserves in the strictest sense). Such estimates involve much less interpretation than do those prepared in the appraisal of the property as a whole, for the position, thickness, quality, and structure of the deposit in the block in question are well known, the cutoff grade has been established, and, in short, the approximate limits of the rock to be mined have already been ascertained.

PROCESSING

Many sedimentary mineral products are in a form suitable for marketing as they come out of the ground. Others require only simple treatment, such as grinding, drying, or sizing, and still others require beneficiation or purification by complicated chemical or mechanical methods. The principles utilized in this phase of mineral production are those of metallurgy and mineral dressing, a field that is well advanced. The geologist, and especially one trained in the methods of sedimentary petrography, may make significant contributions to processing, however, through his knowledge of the texture, composition, mineralogy, and mass properties of the rock, or his familiarity with methods for determining them.

THE FUTURE OF THE FIELD

A candid account of the extent to which geology is actually used, rather than the way it could or should be used, in the production of sedimentary materials emphasizes two observations made previously:

(1) the problems and methods of sedimentary mining geology are so diverse that, though they do not oppose specialization in one field or another, they require intimate knowledge of several branches of geology; and (2) the principles of sedimentation are little used in the production of sedimentary materials, and such principles as are used are elementary in nature. The first of these observations will be as true in the future as it is now, but the second will not be true because the demand for application of geological science will increase markedly in the future for a variety of reasons. (1) New discoveries will be required to offset depletion of known deposits, and to satisfy increased demands created by new uses for many materials (for example, titanium and zirconium) and by expanding markets for others (for example, fertilizers, construction materials, and chemicals). Such discoveries will be increasingly difficult to make by traditional methods. (2) The non-metallic industry is becoming highly competitive and will soon place a higher premium on techniques that will improve the product or lower the cost of mining and transportation. (3) Sedimentary rocks are potential sources of many elements, such as vanadium, nickel, zinc, uranium, and fluorine, now currently mined from deposits of other types. Though sedimentary deposits of these elements do not compare in tenor with other ores and are more expensive to treat, they are cheaper to explore, develop, and mine. They have been little investigated in the past but may be expected to receive an increasing amount of attention in the near future.

That organizations mining and searching for sedimentary mineral deposits have not already called on sedimentation, and geology in general, for more assistance is not wholly because they have not required help, or because they have been unaware of the existence of these sciences. The truth is that the principles of sedimentation are not yet understood or developed thoroughly enough to enable them to be used widely in the exacting prediction required in ore finding and mining. An ample market already exists for the services of geologists who can demonstrate a sufficient knowledge of the principles of sedimenation to find, for example, a gold placer or a high-grade manganese deposit, but few if any geologists are so engaged in making their fortunes. In short, the extent to which geology is used in the mining industry today is at least an approximate measure of its present usefulness.

Admittedly, much more knowledge will be required to place the search for sedimentary mineral deposits on a wholly scientific footing, but considerable progress in that direction could be achieved by use of information already at hand. To what extent have the principles of hydraulics been applied to the search for and exploration of placers, or our knowledge of physical and inorganic chemistry to the search for chemical deposits? For how many minerals has the mode of occurrence of their known deposits—their areal variations in composition and thickness as well as their relationships to the lithologic variations of the enclosing beds, paleogeography, and tectonic history—been analyzed systematically? Of equal importance to the acquisition of additional facts are the systhesis and interpretation of data now available, not only in the literature of geology but of related sciences as well.

In conclusion, the size of the industry, the growing demand for new discoveries, as well as for the application of techniques that will lead to economies of mining, and the rapidly accumulating mass of uninterpreted facts about sedimentary rocks and processes combine to make the field of sedimentary mineral deposits one of many opportunities for geologists primarily interested in sediments.

ACKNOWLEDGMENTS

Whatever understanding I may have of the field of economic geology of sedimentary mineral deposits and of the use currently made of geology in the various phases of mineral exploitation, I owe as much to discussion with friends and colleagues as to my own observations and experience. I therefore wish to acknowledge with thanks the benefit received from many talks on this general subject with D. F. Hewett, M. R. Klepper, A. E. Weissenborn, E. P. Kaiser, E. C. Stephens, O. N. Rove, and especially S. G. Lasky.

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Chapter 28

SEDIMENTARY IRON DEPOSITS

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GENERAL STATEMENT OF PROBLEM

Iron is the second most abundant metallic element in the earth's crust. It occurs combined with other elements to form a large variety of iron-bearing minerals. Most sedimentary rocks contain some iron, but only those that show an unusual concentration (10 percent Fe or more) are included here under the term sedimentary iron deposit. The wide distribution of sedimentary iron deposits throughout geologic time from pre-Cambrian to Tertiary serves to emphasize the importance of the sedimentary processes in which iron participates.

More than 90 percent of the world's production of iron ore is derived from sedimentary iron deposits. Thus a thorough knowledge of sedimentation is a prerequisite for those who wish to specialize in this field.

The primary interest of the geologist or engineer who studies iron deposits from a commercial point of view is to discover large, high-grade bodies of iron ore. It is true that practically every type of iron deposit has been exploited at some time or other in the past, but with the enormous tonnage requirements of the modern steel industry of today we find that only deposits that contain extremely large tonnages of desirable material can be utilized economically. This in effect has practically limited commercial development to the residual deposits formed on or within siliceous iron formations and to the marine oxide deposits. The laterite deposits contain large tonnages of relatively high-grade material, but the presence of undesirable impurities limits their use.

A knowledge of sedimentation is helpful in solving many of the practical problems associated with iron deposits. The problems usually center around variations in iron content, the stratigraphic position, areal extent, shape and thickness of the deposit, the texture, mineral composition, and the presence of undesirable impurities, such as silica, alumina, phosphorus, and sulphur. These physical and chemical properties are largely the result of the environment that existed during or immediately after deposition of the sediment. Because iron deposits form under a variety of environments, these properties may be expected to show considerable range, but fortunately they are rather constant for each specific environment. The sedimentary iron deposits may therefore be grouped according to mineral composition and origin into various types which have physical and chemical attributes in common. This is of practical value, for, if the type of deposit is known, the physical and chemical characteristics may be fixed within fairly well-defined limits. For instance, certain types, such as the bog and placer deposits, tend to be thin, lenticular, and low in grade, whereas others, such as the Clinton and Lake Superior deposits, are remarkable because of their thickness, lateral extent, or lack of impurities. The physical and chemical characteristics of each type of deposit are largely a heritage of the source, mode of transportation, and the environment of deposition of the iron. The geologist must appreciate these genetic factors fully, or he will be without guidance in searching for new ore bodies, carrying out development work, estimating tonnages, or prospecting intelligently for the continuity of known ore bodies either laterally or in depth.

SOURCE OF IRON

Nearly every rock exposed at the surface of the earth contains some iron, but the basic igneous rocks are especially rich in this element. Mechanical and chemical weathering release this iron and make it available as the largest single source for sedimentary deposits. Van Hise and Leith (1911, p. 499) have suggested another potential source of iron. They point out the close association of the pre-Cambrian iron formations with contemporaneous submarine lavas and suggest that the iron was derived directly from magmatic sources, either by magmatic emanations from basic lavas poured out on the ocean floor or by rapid decomposition of these rocks, owing to their contact while hot with sea water.

TRANSPORTATION OF IRON

Iron may be transported mechanically in the form of various iron-bearing minerals, as a colloid, or in true solution.

Mechanical

The mechanical transportation of iron-bearing minerals by traction or suspension may be attended by considerable abrasion and decomposition before final deposition. This tends to concentrate the more resistant minerals, such as magnetite and ilmenite in the form of placer sand deposits, whereas the less resistant iron-bearing minerals are deposited with the silts, clays, and chemical sediments.

Colloid

Gruner (1922, pp. 407–460) and Moore and Maynard (1929, pp. 272–303, 365–402, 506–527) state that iron is transported by present streams mainly in the form of ferric oxide hydrosol stabilized by organic matter. Although the average iron content of river waters in North America is less than 1 part per million, there are many streams and lakes that show a higher concentration. Moore and Maynard (1929, p. 300) have shown experimentally that as much as 36 parts per million of ferric oxide may be held in colloidal solution by 16 parts per million of organic matter.

Solution

Iron may be transported in solution as ferrous bicarbonate, sulphate, or chloride, or as salts of organic acids, provided that the environment is one in which there is a deficiency of oxygen. Ground waters often provide this environment. In moist regions where there is an abundance of decaying organic matter, the ground water removes and transports iron as the bicarbonate. If sulphides are present, ground water is likely to transport iron in the form of ferrous sulphate. When the ground waters emerge at the surface, the ferrous salts are oxidized, and transportation of the iron is principally in the form of colloids. It is possible that in the geologic past the atmosphere may have been largely composed of carbon dioxide and deficient in oxygen. This would allow extensive transportation of iron bicarbonate over long distances.

DEPOSITION OF IRON

Mechanical

Mechanically transported iron-bearing minerals are deposited when the velocity of the transporting medium drops to a critical level, which is specific for the size, shape, and specific gravity of the particle concerned. Incomplete sorting usually leads to the deposition of the heavy iron-bearing minerals with light minerals such as quartz and feldspar, but occasionally the iron-bearing minerals form black sand concentrates on beaches, in river channels, or in sand-dune areas.

Ferric Oxides

Colloidal ferric oxide is precipitated, according to Moore and Maynard (1929, p. 278), by various electrolytes, such as sodium chloride, potassium sulphate, magnesium sulphate, potassium chloride, potassium nitrate, sodium hydroxide, or sea water with a salt concentration of 34,400 parts per million. If the environment of deposition is one in which oxygen is abundant, ferric hydroxide will also be precipitated from ferrous bicarbonate solutions. An exhaustive study by Harder (1919, p. 77) of the bacteria that precipitate ferric hydroxide indicates that they may be classified into three groups: (1) bacteria that require solutions of ferrous bicarbonate utilizing carbon dioxide set free and the available energy of reaction for their life processes; (2) bacteria that do not require ferrous bicarbonate but cause the precipitation of ferric hydroxide when either organic or inorganic iron salts are present; (3) bacteria that attack iron salts of organic acids, using the organic radical as food and leaving ferric hydroxide, or basic ferric salts that gradually change to ferric hydroxide.

Ferrous Carbonate

Iron transported as the bicarbonate may be precipitated as the carbonate (siderite) in an environment deficient in oxygen. Precipitation may be brought about by agitation, decrease in pressure, increase in temperature, bacteria, or the photosynthesis of green plants.

Sulphides

The iron sulphides, marcasite, pyrite, melnikovite, and hydrotroilite, are deposited under reducing conditions from solutions containing various iron salts. Precipitation may be brought about by hydrogen sulphide liberated by decaying organic matter or by the reduction of ferrous sulphate, sulphites, or thiosulphates by bacteria, organic matter, or other reducing agents.

Experiments by Allen, Crenshaw, and Johnston (1912, p. 215) indicate that marcasite forms in acid solutions, pyrite in neutral or slightly acid solutions, and melnikovite in alkaline solutions. Hydrotroilite is a black hydrous monosulphide of iron which is probably deposited as a hydrophyllic colloid.

Harder (1919, p. 41) states that bacteria may bring about the deposition of iron sulphide in four ways. (1) Anaerobic sulphate reducing bacteria obtain oxygen for the oxidation of carbon from sulphates, sulphites, and thiosulphates with the result that these compounds are reduced to sulphides. (2) Calcium or magnesium sulphides formed in an analogous manner by bacteria react with carbon dioxide in the presence of water and are changed to carbonates and hydrogen sulphide. The hydrogen sulphide may then react on ferrous salts such as ferrous bicarbonate in the water and precipitate ferrous sulphide. (3) Putrifying bacteria produce hydrogen sulphide from sulphur-bearing proteins. (4) The reduction of sulphur to hydrogen sulphide by bacteria takes place in the presence of decomposing organic matter.

The iron sulphides, besides forming as a direct precipitate from ferrous solutions, may be formed by the reduction of originally precipitated ferric hydroxide by decaying organic matter.

SILICATES

The iron silicates, glauconite, chamosite, and greenalite occur in sedimentary iron deposits as important constituents, whereas celadonite, berthierite, and thuringite are relatively rare. The formation of these iron silicates, with the exception perhaps of greenalite, appears to be related to diagenesis rather than to direct precipitation from solution.

Glauconite is found on modern sea bottoms and in rocks that were deposited under marine conditions. Hadding (1932, pp. 44–54) concludes that the inferences drawn from geologic evidence indicate that glauconite forms only in a shallow water, sublittoral marine environment in which the waters are agitated and where sedimentation is going on very slowly. The environment seems to be intermediate between strongly reducing and strongly oxidizing. However, the mineral celadonite, which is very similar to glauconite in both appearance and chemical composition, occurs as an alteration product of olivine and also fills vesicules in basalt. Celadonite may be formed from olivine in the late cooling stages (deuteric) of a basalt, as Hendricks and Ross (1941, p. 704) suggest, or it may be of fresh-water origin, as Twenhofel (1939, p. 400) postulates.

The occurrence of glauconite within foraminifera shells lead Murray and Renard (1891, p. 389) to the conclusion that there was a genetic relationship between the shells and glauconite. They concluded that shells of foraminifera became filled with mud containing organic matter. Iron in the mud was altered by the decaying organic matter to iron sulphide. Oxidation of the iron sulphide released sulphuric acid which decomposed the clay, releasing colloidal silica and alumina. The iron, the colloidal silica, and part of the colloidal alumina combined with potash, extracted from the sea water, to form the mineral glauconite. This explanation does not account for the large quantities of glauconite not associated with foraminifera tests.

Galliher (1935, pp. 1351–1366) notes the association of glauconite with partially altered biotite in Monterey Bay off the California coast and suggests that glauconite is formed from biotite by the loss of some alumina, potash, and magnesia, the oxidation of iron, and a gain of water. The granular occurrence of much glauconite is accounted for as follows. The biotite flakes swell greatly during the process of alteration, so that they do not pass freely through the digestive tracts of mud-dwelling worms, but are molded into coprolite granules. It seems probable that glauconite derived from biotite can be of local significance only, for muscovite (the dominant mica in materials derived from crystalline rocks) is absent or rare in many glauconite deposits, and furthermore some greensand beds are nearly pure glauconite. It is probable that the silica, alumina, and iron of glauconite were derived from mud and at least part of the potassium and magnesium were derived from the marine waters.

Little is known regarding the origin of chamosite, berthierite, and thuringite, but most writers assume that they are products of diagenesis. Alling (1947, p. 1012) suggests that the chamosite in the Clinton formation of New York was formed by solutions percolating through the unconsolidated sediments shortly after deposition.

The origin of greenalite is not well understood. Van Hise and Leith (1911, pp. 518–529) suggest that the greenalite in the Lake Superior iron formations was deposited as a chemical precipitate in waters, which received their iron and silica by direct contribution from a magma or by the reaction of sea water with hot submarine lavas. Gruner (1922, pp. 407–460) concludes that the greenalite in the Biwabik formation of Minnesota was formed in a manner similar to glauconite. He suggests that the iron and silica were derived from a basic igneous terrane through normal weathering.

DEPOSITS OF SEDIMENTARY IRON

Sedimentary iron deposits usually consist of one or more iron-bearing minerals associated with non-iron-bearing clastic or chemical sediments. Clays, silts, sands, chert, and carbonates of calcium and magnesium are often interbedded with or act as diluents of the iron-bearing minerals. The various types of sedimentary iron deposits may be classified into four groups: iron oxides and hydroxides, iron carbonate, iron sulphide, and iron silicates; and each group may then be subdivided on the basis of genesis. This classification, although simple, is difficult to apply to iron deposits of complex mineralogy or to those which have suffered alteration since deposition.

IRON OXIDES AND HYDROXIDES

The following oxides and hydroxides of iron are known to form in a sedimentary environment; hematite (Fe_2O_3), magnetite (Fe_3O_4), goethite ($Fe_2O_3 \cdot H_2O$), zanthosiderite ($Fe_2O_3 \cdot 2H_2O$), and limnite ($Fe_2O_3 \cdot 3H_2O$). Limonite ($2Fe_2O_3 \cdot 3H_2O$), according to Posnjak and Merwin (1919, pp. 311–348), is goethite with absorbed and capillary water. Other oxides of iron such as ilmenite and chromite are derived from pre-existing rocks and transported and deposited as clastics.

Mechanical Deposits

Magnetite, ilmenite, and hematite are relatively stable minerals in the environment of weathering. Disintegration or decomposition of a parent rock containing these minerals releases them, and they become a potential source of sedimentary iron deposits. Waves and currents remove the associated lighter minerals and concentrate the heavy minerals as "black sand" or "placer" deposits. The requisite conditions for a natural segregation of heavy minerals is usually local, and therefore deposits of this type are impure, thin, lenticular, and of only moderate lateral extent. The mineral and chemical composition is usually complex, with rare minerals such as gold, platinum, and diamonds often of more economic importance than the iron-bearing minerals. Raeburn and Milner (1927, pp. 90–128) discuss the various factors that control the localization of placer deposits. Black sand deposits have been rather extensively mined in the past along the St. Lawrence River in Quebec and on the coasts of Japan. The deposits on the coast of Florida have been described by Martens (1928, pp. 81–90), and those along the Oregon coast by Twenhofel (1943, 1946).

More important from the economic viewpoint are the mechanical deposits of hematite derived from pre-existing iron deposits. To this group belong the Cambrian conglomerate ores of Missouri described by Crane (1912, pp. 111–112, 127–129), the sand, rubble ore, or canga of Minas Geraes, Brazil, described by Leith and Harder (1911, pp. 670–686), and many of the low-level laterites.

Residual Deposits

Residual deposits of sedimentary iron form on a wide variety of rocks. The original iron content of the parent rock may be low, as in serpentine or limestone, or it may be relatively high, as in the banded siliceous iron formations of the Lake Superior type.

When serpentine is subjected to prolonged weathering in a warm, humid climate, the more soluble constituents are removed from the zone above the water table, particularly in plateau areas with active ground-water drainage, and the less soluble constituents, such as iron and alumina, remain to form a residual deposit termed laterite. The laterite may be ferruginous or aluminous, depending on the relative proportions of the two constituents in the original rock.

Ferruginous laterites usually have a thin upper zone which consists of earthy, oolitic, or pisolitic hematite with a minor amount of magnetite, whereas the main portion of the deposit is limonite. The contact with the underlying serpentine is usually very sharp, but extremely irregular. The irregularity is due to selective weathering of the parent rock along joints or zones of higher permeability. The porosity of a laterite may be as high as 75 percent, but it usually decreases near the surface. The thickness and areal extent of laterite deposits is variable; many are thin and cover a limited area, but others such as the Cuban and the Conakry deposits of French Guinea reach a maximum thickness of 100 and 200 feet, respectively, and form a mantle over an area of many square miles.

The chemical composition of laterite is directly related to the composition of the parent rock. Insoluble constituents besides iron and alumina tend to be concentrated and assume significant proportions in the ore. Laterites derived from serpentine usually contain chromium, nickel, and cobalt, whereas those formed on basaltic rocks contain an appreciable amount of titanium. Gold, tin, copper, diamonds, and other resistant minerals occur in some deposits as important constituents. The iron content of the Cuban laterites, which are of Tertiary age, ranges from 40 to 60 percent, alumina is usually high, and phosphorus, sulphur, and silica are low. These deposits have been described by Kemp (1915, pp. 129–154) and Leith and Mead (1912, pp. 90–102; 1915, pp. 1377–1380), but those of South America, India, Africa, Borneo, the Celebes, and Mindanao in the Philippines are less well known.

Residual iron deposits are also formed on limestones and dolomites under conditions of thorough weathering. Siderite, ankerite, or pyrite disseminated in the parent rock oxidizes to goethite, and large quantities of calcite or dolomite are removed in solution. Other insoluble impurities such as clay and quartz sand accumulate with the goethite and dilute the iron deposit.

The brown ores of Alabama, Georgia, and Virginia are residual deposits of limonite and goethite formed during the Tertiary on Cambrian-Ordovician and Silurian limestones and dolomites. The deposits occur as small, rather thin, irregular lenses surrounded by clay, or as lumps or nodules of limonite in the clay. The deposits range in iron content up to 55 percent, are high in alumina, contain 5 to 30 percent silica, 0.1 to 2.0 percent phosphorus, 0.3 to 10.0 percent manganese, and are low in sulphur.

The Tennessee River brown ores occur as pockets in residual clay and as nearly horizontal mantles on lower Carboniferous limestones.

The deposits of Bilbao, Spain, differ from the normal residual iron deposits on limestone in that they are high-grade and low in impurities. This is due to an unusual situation. A 250-foot bed of Cretaceous limestone has been hydrothermally replaced by masses of siderite with minor ankerite and sulphides. Weathering of the iron-bearing minerals has produced surficial blankets of residual iron oxide, the largest of which is about 100 feet thick and about 2 miles long and three quarters of a mile wide. The oxidized ore ranges from 50 to 57 percent in iron and is of bessemer grade.

The brown ores of eastern Texas are residual deposits formed by ordinary weathering processes on the Weches glauconite of Eocene age. The ore occurs as a horizontal blanket 3 to 4 feet thick resting on white clay, which grades downward into weathered glauconite; or it occurs as nodules or thin lenses in a 5- to 30-foot zone of greensand. The ore contains 42 to 48 percent iron, 10 to 12 percent silica, 8 to 12 percent alumina, and less than 0.24 percent phosphorus.

The great iron deposits of the Lake Superior region are the leached portions of former sedimentary iron beds. Silica and other substances have been removed by circulating ground waters from the iron-bearing formations resulting in a residual concentration of iron oxide. These deposits, which include the Mesabi, Vermillion, and Cuyuna in Minnesota, the Gogebic in Wisconsin and Michigan, and the Marquette and Menominee ranges in Michigan, have produced over 2 billion tons of iron ore. The original pre-Cambrian iron formations consist of siderite, greenalite, hematite, and chert, and average about 28 percent in iron. Van Hise and Leith (1911, pp. 539–540) conclude that the ore was formed by pre-Cambrian surface waters which leached the silica of the chert, leaving a residual mass of porous hematite and limonite. Gruner (1937, pp. 121–130), on the other hand, has suggested that the leaching of the silica was mainly effected by hydrothermal solutions. The ore, which extends to depths of 3,000 to 4,000 feet locally, occurs as large blanket deposits on the Mesabi, above the intersection of basic dikes with impervious horizons on the Gogebic and Marquette, above large basic sills on the Marquette, and in synclinal troughs on the Menominee range. The ore bodies generally lie on impervious rocks, such as slate, that guided and controlled the ground-water circulation. The permeability and the iron content of specific sedimentary horizons seem to have played an important role in localizing the ore. In general, the more permeable horizons permitted more extensive leaching of silica, and the horizons with a higher original iron content required less leaching to form a high-grade ore.

The composition of the ore varies considerably even within the limits of one mine. The iron content of the direct-shipping ore ranges from 38 to 66 percent. Sulphur is generally low but ranges from a trace to 2.0 percent; phosphorus ranges from 0.008 to better than 1.0 percent and averages about 0.09 percent; silica ranges from 2 to 40 percent and averages about 8.5 percent; alumina ranges from 0.16 to 6.0 percent; and moisture averages about 11 percent. The ores range from 7 to 20 and average about 12 cubic feet per ton. Manganese is important only on the Cuyuna range, where it ranges from 5 to 20 percent.

Residual deposits of limonite also form as surface oxidation products on sulphide deposits. These are called gossans. The sulphide deposits (pyrrhotite, pyrite, chalcopyrite, sphalerite, bornite) at Ducktown, Tennessee, illustrate extreme surface weathering. Oxidation and leaching have changed the sulphide ores near the surface into a porous, cellular gossan consisting essentially of limonite with a little silica, kaolin, and a fraction of a percent of copper and sulphur. Limonite of this type has been mined at Rio Tinto, Spain, Shasta County, California, and at various localities in Missouri.

Marine Deposits

Marine deposits of iron oxide are widely distributed geographically, as well as throughout the geologic column. Some of the largest and most extensive iron deposits of the world are of this type. These deposits seem to have been formed in shallow epeiric seas surrounded by low-lying land masses, which furnished little if any clastic sediments to the areas of iron sedimentation. The presence of ripple and current markings and mud cracks indicate that the waters were very shallow. The alternation of shale and sandstone beds with the iron-bearing sediments indicates that from time to time the conditions were such that clastic sediments could be transported in relatively large quantities to the sites of deposition. This in effect terminated the periods of iron deposition.

The deposits consist of hematite or limonite, which may occur either in the form of oolites, as replaced fragments of fossils, or as a fine powder. Calcium carbonate, silica, phosphorus, and clay are usually present as impurities. The calcium carbonate occurs both as chemically precipitated calcite and as fragments of fossils. Siderite is usually absent, and the sulphur content is normally low. The iron content ranges from 10 to 50 percent.

Some of the larger marine oxide deposits include the Wabana hematites of Bell Island, Newfoundland (lower Ordovician), the Neda hematites of Wisconsin (upper Ordovician), the Brassfield hematites of Kentucky (lower Silurian), the Clinton hematites of the Appalachian region (Silurian), the hematites of eastern Kentucky (middle Devonian), the Minette ores of Alsace-Lorraine (middle Jurassic), and the limonites and hematites of Salzgitter (Cretaceous) and the Lahn-Dill (Devonian) deposits of Germany.

The Clinton ores of the Appalachian region rank second in importance to the Lake Superior deposits. The ores are interbedded with shales, limestones, and sandstones and occur as thin, but rather extensive, lenses at slightly different stratigraphic horizons in the Clinton. In the Birmingham district of Alabama, where the ores are extensively mined, there are four beds which thicken and thin from 30 feet to a few inches. The Big Seam at Birmingham outcrops for a distance in excess of 20 miles and ranges from 16 to 40 feet thick, of which 7 to 12 feet is minable. There are two main types of ore in the Clinton: (1) fossil ore, composed of fragments of fossils partially or completely replaced by hematite, set in a matrix of powdery and oolitic hematite; (2) oolitic ore consisting of spherules of hematite 1 to 2 millimeters in diameter with a rounded sand grain or fossil fragment as a nucleus, set in a matrix of powdery hematite, fossil fragments, and calcite. The oolites are often flattened and resemble flaxseed. This type is referred to as the flaxseed ore. The ore, when encountered at depth, ranges from 20 to 40 percent iron, is hard, and averages about 15 percent silica. Near the surface (0 to 400 feet) the carbonate has been leached to produce an enriched "soft ore," which may contain 50 to 60 percent iron and 12 percent silica. The ores are high in lime, alumina, and phosphorus.

Although the Clinton ores have long been recognized to be of marine origin, the environment of deposition of the iron has received considerable discussion. Alling (1947, p. 1012) concludes that the iron replaced carbonates shortly after deposition, as part of the diagenesis of the sediment. Others have concluded that the hematite was deposited originally in the powdery or oolitic form or that the hematite replaced the carbonates long after deposition.

The Wabana ores are similar in many respects to the Clinton deposits. The hematite is in the form of oolites, but according to Hayes (1915, p. 25) considerable siderite and chamosite are present. Fossil fragments are abundant, but they have not been replaced by hematite. Ripple markings, cross-bedding, and worm burrows are excellently preserved in the ore; they indicate shallow, marine conditions of deposition. There are six iron-bearing beds of which three have been worked commercially. The Dominion bed normally ranges in thickness from 12 to 20 feet but locally reaches a thickness of 35 feet. The ore averages about 9 cubic feet per ton. The iron ranges from 20 to 57 percent, the alumina from 3 to 6 percent, the phosphorus from 0.7 to 2 percent, the lime from 1 to 3 percent, the silica from 6 to 50 percent, and the sulphur is very low.

The oolitic Minette limonites occur as lenticular bodies interbedded with shales, limestones, and sandstones. Seven ore horizons occur, ranging in thickness from a few inches to 25 feet. The ore is soft, earthy, oolitic limonite and hematite with some siderite and chamosite. The limonite has been generally regarded as a primary deposit, but Cayeux (1909, p. 284) concludes that calcite oolites were replaced by the iron oxides. The ore averages 30 percent iron and contains 0.5 to 1.8 percent phosphorous, 5 to 12 percent lime, and 7 to 20 percent silica.

The Bavarian and Württemberg oolitic ores of Germany are mainly sedimentary limonites but contain some siderite and hematite. The high-phosphorus Salzgitter ores occur in thin beds and contain about 30 percent iron and 25 percent silica.

Bog Deposits of Limonite

Bog iron ores are formed in swamps, lakes, and sluggish streams. They consist of dark-brown, cellular, or oolitic masses of limonite with some hematite. Iron silicates, iron sulphides, iron phosphate, siderite, organic matter, and clay or sand occur in the ore in variable amounts. Plants and roots are often replaced by limonite. Deposits of this type are thin and have a very limited lateral extent. The ores are usually mixed with clay and sand and rarely contain as much as 50 percent iron. Silica, alumina, and phosphorus are usually present in relatively large quantities, but sulphur is normally low. Bog iron ores are now of slight importance to the mining industry because of the small size and the impurity of the deposits. Bog deposits have been mined at many localities throughout the world. It is of interest to note that

Griffen (1892, p. 985) states that 15 feet of concretionary ore was mined from the bottom of Lac-a-la-Tortue near Rodnor Forges, Quebec, and that 10 years later sufficient limonite had accumulated to make it profitable to mine again.

IRON CARBONATE

Iron carbonate occurs only as the mineral siderite ($FeCO_3$). Siderite is found in sedimentary deposits as concretions, lenses, and beds associated with shales, sandstones, limestones, and chert. Iron carbonate deposits are in general low in grade and rarely contain more than 40 percent iron. This is due to the relatively low metallic iron content of siderite (48.2 percent) and to the presence of impurities, such as organic matter, clay, sand, chert, and calcite.

Thin beds of iron carbonate which have great lateral extent are commonly associated with coal measures. Deposition apparently took place in brackish marine waters or in marine swamps where abundant decaying vegetation inhibited oxidation of the iron and promoted the formation of siderite.

The concretionary ironstones, sometimes referred to as "kidney ores," are spherical to disk-shaped, laminated concretions composed of siderite, calcite, and clay. They are abundant at certain horizons in the Permian shales and sandstones of Pennsylvania but are not of economic significance.

The blackband ores consist of thin beds and lenses (usually less than 1 foot thick) of siderite interbedded with clays and shales. The black color is due to organic matter. Blackband ores are especially abundant in the Mississippian and Pennsylvanian rocks of the Appalachian coal fields. They also occur in England and Germany. There are 75 horizons of siderite in the lower coal measures of Wales. Blackband deposits are not of economic importance today because of their low grade (25 to 40 percent iron). They are high in sulphur and phosphorus, and they occur in thin beds.

Siderite occurs as oolites associated with chamosite in shales and sandstones of Jurassic age in the Cleveland Hills of England. The ore bodies that are mined range from 6 to 25 feet in thickness and average about 28 percent iron. They contain about 15 percent silica, 11 percent alumina, and 1.0 to 2.0 percent phosphorus.

Van Hise and Leith (1911, p. 500) state that the pre-Cambrian iron formations of the Lake Superior region were originally composed of alternate laminae of chert and siderite, with subordinate but locally important quantities of greenalite and hematite. Subsequent oxidation of the siderite and greenalite has produced the ferruginous cherts and jaspers, which consist of alternate beds of iron oxide and chert. The siderite-chert deposits which are observed today in these iron formations have been protected from oxidation and are thus the remnants of much more extensive deposits. The well-developed bedding of the iron formations and the gradation laterally and stratigraphically into sands and shales indicate deposition in standing bodies of water. Van Hise and Leith (1911, p. 516) suggest that the iron and silica was either contributed to the areas of deposition directly from a magmatic source, or that the iron and silica were released by the reaction of hot submarine lavas with sea water. Gruner (1922, pp. 459–460) is of the opinion that the iron and silica were derived from the thorough weathering of an adjacent land mass composed of basic Keewatin lavas and deposited as chemical sediments in a standing body of water. Woolnough (1941, pp. 465–489) suggests that deposition may have taken place in isolated basins on a peneplane surface during periods of low seasonal rainfall.

The siderite iron formation and its oxidized equivalents provide an enormous tonnage of low-grade siliceous material which averages about 28 percent iron. Although these deposits are not being used extensively at present, they represent a vast reserve of iron from which high-grade concentrates may be manufactured through the use of proper ore-dressing techniques.

IRON SULPHIDES

The iron sulphides—pyrite (FeS_2), marcasite (FeS_2), melnikovite (FeS_2), and hydrotroilite ($FeS \cdot nH_2O$)—form in a sedimentary environment. These minerals usually occur as aggregates or individual grains disseminated through sedimentary rocks, and they do not form important deposits of iron. Iron sulphides are particularly abundant in coal deposits and in carbonaceous shales and slates.

Thin sedimentary beds of oolitic pyrite or marcasite are associated with the oolitic hematite ores of Wabana, Newfoundland, and the sideritic ores of Cleveland Hills, England, but they are not of economic importance at present. The oolitic iron sulphide deposits of Meggen, Germany, range from 12 to 20 feet in thickness and are associated with Devonian limestones and slates. They have been worked for the iron sulphide content.

IRON SILICATES

Greenalite, glauconite, and chamosite are the most common iron silicates formed in a sedimentary environment. Thuringite, berthierite, and celadonite are relatively rare.

GREENALITE

Greenalite occurs associated with chert and siderite as an important constituent of the pre-Cambrian Biwabik iron formation of Minnesota, but it is rare to absent in the pre-Cambrian iron formations of Michigan and Wisconsin. It has been reported by Hadding (1929, p. 236) from Liassic sandstones of Sweden and by Kennedy (1936, pp. 433–436) from the Ordovician of Scotland; and the writer has observed a greenalite-like mineral to be associated with chert in the iron formation of northern Labrador. Greenalite normally occurs as dark-green ellipsoidal granules 0.1 to 1.0 millimeter in diameter, embedded in a matrix of chert and siderite. The rock usually ranges from well-bedded to massive and averages about 28 percent iron.

GLAUCONITE

Glauconite is the most widely distributed iron silicate. It rarely is found as a pure deposit but occurs in shales, sandstones, and limestones of all ages from Cambrian to present marine sediments. Glauconite occurs as granules and in the form of pigmentary powder. Pure glauconite rarely contains as much as 20 percent iron, and since it is often associated with clay, sand, or phosphatic shell fragments it forms low-grade, but rather extensive, iron deposits.

There are three beds of rather pure glauconite in the Cretaceous series of New Jersey which range individually from 10 to 50 feet in thickness and aggregate about 90 feet. The area of these deposits is about 120 miles in length by 40 miles in width. Eckel (1914, p. 56) estimates that the total glauconite in the Cretaceous series contains 250 thousand millions of tons of iron oxide. Glauconite beds that have been subjected to surface weathering, such as the Weches horizon of east Texas, may be enriched sufficiently to form limonite ores.

CHAMOSITE

Chamosite is often associated with berthierite, thuringite, and siderite. Chamosite is present in the Wabana ores of Newfoundland, the Minette ores of Lorraine, the Jurassic ores of the Cleveland Hills, England, and to a limited extent in the Clinton ores of the Appalachian region.

RESEARCH NEEDED

Although the general source, methods of transportation, and modes of deposition of iron are well-known we are often at a loss to outline the origin of specific iron deposits with any exactitude or to explain why given types of deposits were formed only during certain geologic periods. The Clinton type of iron deposit is certainly of marine origin, but where was the source of the iron, how was it transported to the site of deposition, and as what mineral and under what chemical conditions was it deposited? Hawley and Beavan (1934, p. 510) concluded from a study of the Mayville ores of eastern Wisconsin that ". . . the ore minerals throw no light on the baffling problem of their source," although the presence of clastic grains of fragmental lava suggests derivation from a pre-Cambrian volcanic terrane.

It is often difficult to determine the identity of the original iron-bearing minerals, because subsequent oxidizing or reducing environments, during diagenesis or at a much later date, may have materially altered the mineral composition of the deposit. For instance, Van Hise and Leith (1911, pp. 529–537) state that the original siderite and greenalite of the pre-Cambrian iron formations of the Lake Superior region were extensively oxidized to hematite and limonite long after deposition. Perhaps this also is true for other iron deposits.

There is often question why the pre-Cambrian iron formations are characterized by the association of greenalite, siderite, and chert, whereas the iron deposits of later geologic periods are composed of hematite, limonite, chamosite, glauconite, or siderite and are not associated with chert. These are fundamental problems which must be answered before we shall be able to understand fully the origin of sedimentary iron deposits. Furthermore, many of the pre-Cambrian sedimentary iron deposits, such as the itabirite of Brazil and Venezuela and the ferruginous quartzites of South Africa and Australia, have been described as alternating laminae of iron oxide and clastic quartz. Recent studies by Tyler (1948, pp. 86–87) indicate that the "clastic quartz" of the Brazilian deposits is recrystallized chert. The mineral composition of the original iron-bearing materials is unknown. Additional studies are needed to clarify these problems.

Other lines of research of perhaps a more practical nature are those that lead to a more concise explanation of the origin of the higher grade deposits and the physical and chemical factors that localized them. The laterites present many problems of this nature. Under what specific chemical and physical conditions do laterites form, and where are deposits of laterite most likely to be found? Although laterites have been studied very extensively, Reiche (1945, p. 66) states that ". . . concepts of weathering under tropical conditions are apparently in a state of discouraging confusion." Additional research is also needed to explain the localization of the oxidation and leaching that resulted in the formation of the ores of the Lake Superior region. Studies of this type may lead to the discovery of new, high-grade deposits.

Further research is also needed on the mineral composition of sedimentary iron deposits to ascertain the manner of occurrence and distribution of phosphorus, sulphur, nickel, and other elements deleterious to the economic use of the material. Furthermore, as depletion of the higher grade iron deposits necessitates the use of lower grade materials, beneficiation becomes of more immediate importance. A more thorough knowledge of the mineral composition and texture of the iron-bearing and associated gangue minerals is a necessary prerequisite to ore-dressing problems.

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Chapter 29

SEDIMENTARY ROCKS AS HOSTS FOR ORE DEPOSITS

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LIMITATIONS OF TOPIC

This discussion is limited, by agreement, to a consideration of sedimentary rocks as receptacles for the subsequent deposition of ores and of the factors that determine what kinds of rocks are effective hosts in particular circumstances. Some of these features, naturally, result from the sedimentation processes that formed the rocks and, therefore, are germane to a general consideration of problems of sedimentation. Obviously excluded from this survey are all syngenetic bedded ores, which are covered in another part of this book. Likewise excluded, since they are covered in another chapter, are the so-called sedimentary iron ores, even though sometimes there may be a difference of opinion as to whether these are strictly syngenetic or in part epigenetic.

Thus delimited, there remain within our purview three quite dissimilar types of deposits which occur abundantly in sedimentary rocks: (1) residual concentrations, (2) vein deposits, (3) primary replacements.

RESIDUAL CONCENTRATIONS

Ores form by residual concentration in both igneous and sedimentary rocks but are commonest in the latter. They comprise principally ores of the commoner metals which are widespread in the earth's crust, notably iron, manganese and aluminum. However, they include important deposits of less abundant minerals such as phosphates and barytes, and occasional important bodies of non-ferrous metals, particularly copper, zinc, and lead in oxidized forms.

The residual ores of iron, aluminum, phosphorus, and, frequently, manganese form mainly by the concentration of uneconomic amounts of these materials originally dispersed in sediments where, often, they may have been formed syngenetically. The ores of copper, zinc, lead, and barytes, on the contrary, represent concentrations from epigenetic fissure veins or replacements, often of originally uneconomic character but not always so.

The formation of ore deposits by residual processes depends usually on some pronounced difference in the solubility in ground water of the desirable constituent and its accompanying gangue. Either the desirable element ordinarily is much less soluble, or by oxidation it passes into a less soluble form, while the gangue is dissolved and removed. As limestone (including dolomitic types) is by far the most soluble common rock, it follows that residual ores develop most often from limestone terranes. Thus formations containing iron or manganese carbonate are dissolved, the iron and manganese being converted, in the process, to the less soluble oxides and left behind or transported but slightly. Many deposits in the southern and eastern United States, as well as elsewhere, are of this origin. When limestones contain phosphate, which is less soluble than the carbonates, preferential solution produces residual phosphate ores, as in Tennessee and Florida. Two of the important barytes districts of the United States, in Missouri and in Georgia, produce mainly residual ores derived from lean fissure and cavity fillings in limestone formations. Important zinc deposits in the eastern United States from Pennsylvania to Tennessee have consisted of carbonate ore formed from the oxidation of sulphides and their redeposition as carbonate. This differs slightly from the usual process in that it involves replacement of limestone at the base of the weathered zone. Copper ores in the southwestern United States have formed in somewhat similar process as carbonates. Sulphide iron can, by oxidation, also form oxide, or carbonate, deposits, but these are generally small, as large iron sulphide bodies in limestone are not abundant. The Missouri sinkhole marcasite deposits are an exception, and they are often altered to iron oxide.

Aluminum ores such as bauxite and high alumina clays commonly result from the alteration of various types of clay and shale or of calcareous rocks containing large amounts of aluminous impurities. To form ore, the preferential removal of silica often is as essential as the elimination of carbonate, and the inability to remove iron oxide often results in a low-grade or uneconomic deposit. In some places, alluviation processes have affected the residual matter and perhaps form a step in the process of ore formation.

Rainfall, naturally, is an essential in all these residual processes, and to form aluminous ores it apparently needs to be copious. Probably, also, warm climatic conditions are most favorable. However, rainfall, topography, and plant cover must combine in most situations to prevent appreciable erosion so that the residual products will not be removed as they are formed.

Since the area exposed to leaching and oxidation is greatest the more nearly the rocks are flat-lying, and also since erosion is least the flatter the topography is, it follows that most important bodies of residual ores occur in areas of relatively flat-lying rocks and extend only to shallow depths, usually not beyond 100 or 200 feet, often much less. They may, however, be covered by a mantle of uneconomic overburden, due to excessive leaching, subsequent alluvial cover, or other factors. Contacts between unlike formations, as between limestone and shale, or even sandstone, often provide favorable surfaces for the concentration of residual deposits.

The carbonate and oxide ores of lead, zinc, and copper are an exception to the preceding rules, for they may form at considerable depths, especially in arid regions.

There are many interesting chemical and physical problems connected with the formation of these deposits, and they have received much attention, which has proved quite rewarding. However, they seem to have no very pertinent connection with the importance of sediments as hosts for ore and are hardly appropriate to this discussion. Good summaries of residual processes will be found in several textbooks, notably Lindgren (1933) and Bateman (1942).

VEIN DEPOSITS IN SEDIMENTARY ROCKS

Sedimentary rocks are important as hosts to veins of infinite variety, embracing virtually the entire category from pegmatites and quartz veins, with or without economic accessories, through the carbonate series, mineralized or barren, to barite, fluorite, etc. All of these may occur in non-sedimentary rocks as well, and in many localities similar veins occur in both igneous and sedimentary rocks. Indeed, it has long been recognized that sedimentary rocks in the vicinity of intrusive igneous bodies are in a highly perferred position for receiving the mineralizing and vein-forming materials which so often follow closely the final phases of igneous activity. This is due in part, no doubt, to their contrasting physical and chemical nature with respect to the igneous rock, but perhaps even more to the sharp cooling effect they exert on emanations escaping from the heated areas of igneous activity.

Many veins, particularly the stronger quartz and pegmatite varieties, cut indiscriminately across igneous-sedimentary contacts. In the sedimentary rocks they eventually die out, gradually changing character according to general rules, such as from coarse-veined quartz to fine-grained chalcedony, accompanied by irregular silicification effect on the wall rocks. These changes, however, are not likely to be well exhibited within the limits of a particular vein system or locality; they are apparent only from a study of broad regional patterns.

Other veins, such as those of barite and fluorite, are found much more often within sedimentary rocks than in igneous rocks, and often far from any known intrusives of possible relationship. This is true also of many carbonate veins.

With respect to all these diverse types of veins, the chief importance of the sedimentary rock as a host lies in its bedded character and the resultant alternation of competent and incompetent types. As a rule the veins form freely only in competent rocks, which were strong enough, under the load they happened to carry at the depth of vein formation, to maintain openings of visible size and good continuity. They may be essentially free of rubble and breccia fragments or filled with these in nearly any degree so long as good continuity for the flow of mineralizing fluids is achieved. It follows, therefore, that hard or brittle rocks, such as quartzite, or sediments hardened to a considerable degree by metamorphism, are much better vein hosts than soft shales and unconsolidated sediment. Competent rocks with low porosity, also, are better hosts to veins than porous sediments which tend to divert the fluids from vein fractures into lateral bedding planes. Unmetamorphosed limestones are of intermediate character, reasonably favorable receptacles in some cases, particularly when they are massive and thick-bedded; poor in many places, especially if thin-bedded and shaly in nature.

As bedded formations are always of limited thickness and likely to alternate in thin successions, it follows that vein formation is favored when the attitude of the beds somewhat accommodates the tendency of vein material to rise, and is inhibited when beds lie flat or otherwise athwart the general course of any given vein. A series of flat-lying rocks traversed by vertical veins makes for interruptions in continuity and values. Productive portions are likely to be restricted to limited vertical stretches within competent horizons. Under these conditions the value of a particular favorable horizon is likely to be proportionate to its thickness. A steeply dipping series of sedimentary beds with some brittle and competent members favors continuity of vein structures and values over a good vertical extent. Some examples of the two classes are listed below. It will be noted that the veins

Veins Generally Across Bedding	Veins More or Less Along Bedding
Kentucky-Illinois, fluorspar	Coeur d'Alene, lead-zinc-silver veins, Idaho
S.E. Ontario, post-Cambrian lead-zinc veins	Mother Lode gold veins, California
Park City, Utah, in Weber quartzite	Homestake gold veins, South Dakota
Cobalt, Ontario, silver veins	Southern Appalachian gold veins, in part
Barite and fluorite veins of England	Spanish lead veins (Linares)
Chañarcillo silver, Chile	

along bedding are generally of a deeper-seated type than those formed across bedding and are apt to combine features of both fissure filling and replacement in varying degrees.

There seem to be no good general references on the subject of the contrasts between veins in sedimentary rocks and other types, a topic that might be worthy of summation. Much detail will be found in the literature of individual districts where both types are present, particularly in the western United States and Canada.

REPLACEMENT DEPOSITS

General Survey

From the standpoint of number, importance, and scientific problems presented, the replacement deposits are the chief focus of our attention. Replacement of sedimentary rocks or of sedimentary rocks that subsequently have been metamorphosed is found in many mining districts. A similarly important group of replacement deposits, however, shows little or no relation to sedimentary rocks. Well-known representatives of each group are listed below. An inspection of this rather impressive list of deposits in sedimentary rocks makes it apparent at once that it includes a large proportion of the world's great lead-zinc districts. There are a few clear exceptions such as the Buchans mine and Bawdwin in igneous rock. Some districts, such as the Coeur d'Alenes district, are hard to classify. In the Coeur d'Alenes area sedimentary rocks have been cut by fissure veins, though in places they have been replaced, chiefly however as a result of previous vein filling. The Linares district of Spain is somewhat similar. The Tennessee-Virginia zinc deposits may be questionable in that they involve probably more filling of breccia spaces than actual replacement, but they are commonly accepted as replacements. The Joplin district, likewise,

SOME MAJOR REPLACEMENT DEPOSITS

In Sedimentary Rocks	In Non-sedimentary Rocks
Mississippi Valley deposits (S.E. Missouri, lead; Joplin region, lead-zinc; Wisconsin-Illinois, lead-zinc)	Pre-Cambrian iron ores, Missouri
Appalachian zinc deposits (East Tennessee; S.W. Virginia; Friedensville, Pa.)	Tennessee copper (Ducktown)
Pre-Cambrian limestone replacements, eastern U. S. and Canada (Franklin, N. J., zinc; Edwards-Balmat, N. Y., zinc; eastern Ontario and Quebec, lead-zinc replacements)	Appalachian and Adirondack magnetites
Michigan copper (in conglomerates)	Buchans, N. F., copper-lead-zinc
Sullivan Mine, B. C., lead-zinc	Ontario-Quebec copper-gold-zinc replacements (Noranda, etc.)
Kennecott, Alaska, copper	Also Manitoba copper-zinc (Hudson Bay, etc.)
Metaline Falls, Wash., lead-zinc	Sudbury, Ontario, nickel-copper
Leadville, Colo., lead-zinc	Michigan copper (in lavas)
Utah lead-zinc, in part (Park City, etc.)	Cerro de Pasco area, Peru (in part)
Central New Mexico, lead-zinc	Burma, lead-zinc (Bawdwin)
Mexican manto deposits (lead-zinc in limestone)	All porphyry coppers of western U. S. (Bingham, Utah; Santa Rita, N. M.; Ajo, Ariz., etc.)
Aguilar, Argentina, lead-zinc	
Broken Hill and Mt. Isa, Australia, lead-zinc	
Silesian lead-zinc	
Rhodesian copper deposits	
Rio Tinto, Spain, copper-pyrites	
Many pyritic replacements (Appalachians, etc.)	

is more an example of cavity filling (solution cavities) than of actual replacement, but the cavities are generally regarded as a result of the processes by which ore deposits were emplaced in a particular formation. If these qualifications are accepted, our list covers the field of important lead-zinc mines fairly well.

Probably the most important second group, if it were detailed in full, is the pyritic replacements, in part called fahlbands, which are far more numerous than indicated but are apt to be ignored because few of them can be exploited economically. Pyritic deposits can occur in sedimentary rocks of normal facies (Missouri sinkhole fillings, etc.) but are most typical in substantially metamorphosed rocks, very commonly of schistose or slaty character, as at Rio Tinto and in the Appalachian region.

More important economically, at present, are the enormous copper sulphide replacements of Rhodesia and adjacent Central Africa.

There are, finally, a few accessory mineral deposits that may deserve mention. One type is that of barite replacements, as at Magnet Cove, Arkansas. These may be more important than is appreciated, having been overlooked to some extent in the past. A related group is that of bedded fluorite replacements such as the Kentucky-Illinois district, in part.

With respect to the types of rock involved, if we include the various stages of dolomite in the general term limestone, the list has a high proportion of limestone replacements. The Sullivan Mine, British Columbia, and Mount Isa, Australia, are the only important exceptions in lead-zinc. With the pyritic sulphides this situation is distinctly reversed. All the great fahlbands are in siliceous-aluminous rocks; so also with the copper deposits for the most part, although Kennecott, Alaska, and Cerro de Pasco area, Peru, including Morococha, etc., are exceptions.

We thus arrive at the conclusion that the subject of sedimentary rocks as hosts for ore deposits is largely a study of the whys and wherefores of replacement; replacement of limestones by lead and zinc sulphides, and of shales, slates, or schistose rocks by pyritic and cupriferous sulphides.

Lead-Zinc Replacements

On the subject of lead-zinc replacements in limestone, a vast amount of specific literature covers mainly the empirical problems of individual districts. There are also some important papers by way of summation (Van Tuyl, 1916; Hewett, 1928; Hayward and Triplett, 1931; Brown, 1947b; Behre, 1947; Newhouse, 1942).

Several of the references cited deal extensively with the subject of dolomitization as a factor in ore localization. As Behre has pointed out, the conclusions are by no means exact or satisfactory. Dolomitized rock, on statistical evidence, would seem to be much more favorable for ore deposition than pure limestone, although exceptions do occur. But in many instances it still is undetermined whether dolomitization occurred during the diagenesis of the sedimentary rock (and hence long antedating ore emplacement) or only shortly preceding ore deposition and, therefore, probably as an early stage of that process. In either event it seems likely that the preference of ore for dolomite over pure limestone rests on a physical basis more than on chemical factors. Much the same conclusion must be drawn with respect to the importance of magnesian silication (by diopside, tremolite, talc, serpentine, etc.) in metamorphosed limestone formations. Silication of this type usually develops preferred zones for ore and is likely to have occurred long before ore deposition and over areas so broad as to indicate little more than that ore fluids found such areas to be preferred sites, again mainly for physical reasons. In nearly all cases, local, and generally minor, structural features are of prime importance in localizing deposits within particular portions of the favorably dolomitized or altered host.

This leads to a second, and somewhat more satisfactory, generalization on the subject of structural control, namely, that the presence of a fine-grained or otherwise impervious cover above a suitable limestone (or dolomite) host has a marked tendency to localize deposition in the nearby parts of the underlying formation, and probably more so the more nearly the rocks are flat-lying. Good examples are: (1) The Tristate district of Missouri-Kansas-Oklahoma, where ore occurs chiefly in the first 300 feet of Mississippian limestone beneath Pennsylvania shale, which was almost certainly quite thick at the time of deposition although now largely removed by erosion; (2) Leadville, Colorado, where thick porphyry sheets in a series of sedimentary rocks seem to serve a similar function; (3) Park City, Utah, where replacement occurs chiefly in a rather thin zone of Paleozoic limestone beneath thick Triassic shales; (4) the bedded fluorspar deposits of Kentucky-Illinois, where ore occurs in Mississippian limestone beneath thin, shaly members of the same series, and not far beneath a former thick cover of Pennsylvanian shales.

It is commonly accepted that the impervious cover has acted as a guide and confining medium for rising ore fluids, channeling them for long distances within a favorable host rock. The quite different interpretation that the ore fluids actually circulated across the beds and that the ore substances were held back while the transporting fluid continued on, somewhat as in osmosis, has been advanced (Mackay, 1946) but can be accepted generally only with much more convincing proof. The evidence of oil and gas pools trapped beneath similar barriers for millions of years, even though under great pressure and probably by nature more penetrant in some cases (especially gas) than an aqueous solution, seems to be a strong argument against this proposal.

Another lithologic situation that seems to be of considerable importance in some places is the presence of a favorable limestone host above a porous sandstone formation. An outstanding illustration is the southeastern Missouri lead district. Ore occurs in the lower part of the Bonne Terre dolomitic limestone above the Lamotte sandstone, which rests on an irregular pre-Cambrian basement. There may be some question whether the presence of the sandstone or the proximity of the crystalline basement is the more important factor, but apparently ore deposits at this horizon are almost unknown where the intervening sandstone is absent.

This district also serves well to illustrate the great importance of minor or even trivial features in localizing ore where preferred structures are lacking. Many of its deposits are known to be controlled structurally by slight domes of initial sedimentation plus differential compaction, overlying buried knobs in the pre-Cambrian basement. A typical illustration is given in Fig. 1. Moreover, within ore bodies, rich concentrations may be determined by minute rolls of anticlinal character beneath a favorable ore-bearing band.

A mineralized sedimentary sequence similar to that in southeastern Missouri exists in several places in the United States, as in the Llano-Burnet uplift of Texas, the Arbuckle Mountains of Oklahoma, and near the base of the Cambrian succession at various places in the Appalachians, although these are mostly uneconomic occurrences.

A possible variation of this situation is presented by the Wisconsin-Illinois zinc-lead field, where ore occurs in dolomitized limestone not far above the widespread St. Peter sandstone. The pre-Cambrian basement in this area is many hundreds of feet below the sandstone.

In all these occurrences, there is the question, worthy of more careful evaluation, of the extent to which the sandstone may have served to collect ore fluids and distribute them laterally to favorable structural traps. Usually there is also the possible question whether the presence of the highly pervious sandstone below is of great importance or, rather, whether impermeable barriers not far above, present in most areas, has exercised more control.

The subject of impermeable barriers deserves more careful summation than seems to be available anywhere, but an interesting start has been made by Newhouse (1942), and most textbooks treat the matter in some fashion.

Concerning microscopic structures and details of replacement, considerable valuable information is accumulating. My conclusion in the Edwards-Balmat, New York, district was that microbrecciation seemed to be a major factor in controlling the flow of ore fluids, and that probable continuity of openings seemed much more important than absolute porosity. Rove (1947) attempted to evaluate the physical features of favorable horizons by tests of grinding resistance, crushing strength, toughness, etc., but he failed to develop any conclusive correlations and ended by suspecting that secondary permeability induced by shearing probably was the most important factor in determining channels of circulation. My data tended to show that the needful microbrecciation was likely to be concentrated along contacts of

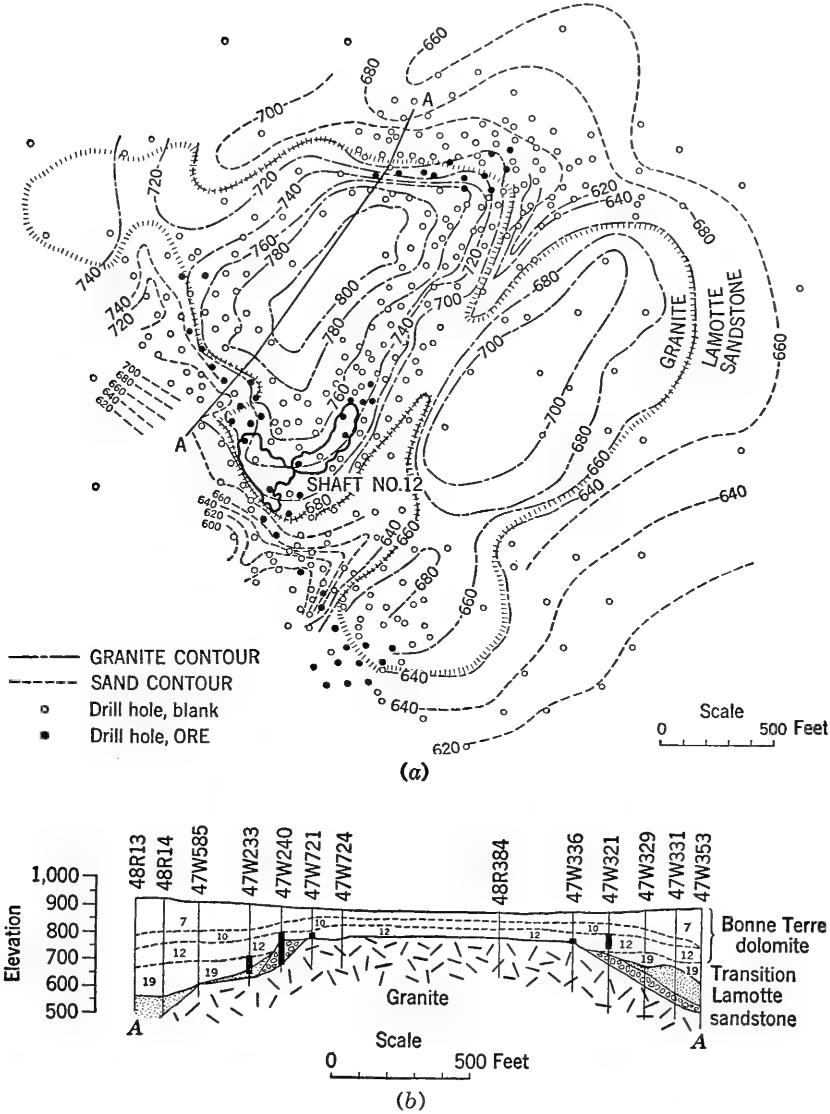

FIG. 1. Ore deposition around a pre-Cambrian granite knob at Doe Run, Missouri; (a) plan, (b) section.

unlike rock masses, and especially in zones of mixed mineral content, as half carbonate and half silicate, rather than in pure mineral types. Rove concluded that effective shearing should be concentrated in rocks of intermediate competence, neither too rigid nor too plastic.

Garrels has in press a paper that deals with extensive tests of porosity and permeability with respect particularly to their relation to diffusion and the possible effectiveness of this process as a step in replacement. The tenor of this is to suggest that diffusion is relatively independent of the size of openings and but moderately affected by total porosity; also that it is rapid enough, especially at elevated temperatures, to be important within reasonable lengths of time.

Ohle also has in preparation a paper covering extensive laboratory experiments on permeability of host rocks carried out under desirable conditions of refinement.

In my own researches and observations, I developed a strong impression that grain size has a very significant influence on ore precipitation, as has been suggested by Bain (1936), who found that in metasomatic replacement from aqueous solutions small capillary openings were much more effective than larger ones, the suggested explanation being that adsorption was an important factor and was proportional to the area of surface exposed. My field observations in some respects tend to support this conclusion, for many fine-grained rocks appear to be especially effective precipitants for ore. Such rocks, however, are not good channels for the transportation of ore fluids over long distances, for which larger openings, even though of microscopic size, and better continuity are essential. But, at the site of deposition, minute subcapillary openings may be very effective. This feature is nicely illustrated in the southeastern Missouri lead district, where the prevailing host rock is a recrystallized dolomite with a grain size of the order of 0.1 to 0.3 millimeter and considerable porosity, quite commonly in the visible range. Intercalated in this type of rock are minor areas of dark shaly material, which may be either in well-defined layers or in rather irregular masses of conglomeratic appearance, enclosing lumps of dolomite. It is within these conglomeratic shaly layers and on the upper and lower margins of the shaly bands, where they grade into dolomite, that ore is especially likely to be deposited in high concentration. Visible porosity in these rocks may be low or lacking, but the grain size is infinitely smaller than that of the enclosing dolomites, estimated to be in the range 0.04 to 0.01 millimeter. Although grain size probably is important in the explanation of this relationship, it is quite likely that other factors, such as the chemically combined water content of the kaolinic matter in the shale, also were influential in localizing ore deposition in this particular situation.

Pyritic Replacements

A large proportion of the pyritic deposits, such as the fahlband type, occur in rocks that have been moderately metamorphosed and recrystallized and are of siliceous-aluminous rather than carbonate facies. It is my impression (on the basis of no very extensive knowledge) that the fine-grained members of a series often seem more favorable than the coarse-grained types. Whether, if true, this is due to grain size, bed composition, or structural incompetence and amenability to shearing is not definitely known and, so far as I am aware, has not been investigated seriously. The apparent preference for siliceous-aluminous rocks, in contrast to the pronounced tendency of lead-zinc ores to favor limestone, likewise is unexplained. A diversion of some of the research activity centered on limestone replacement into this field or, preferably, a comparable expansion of interest into this phase of mineral deposition seems quite desirable.

CONCLUSION

In conclusion, it may be remarked that this discussion has been limited, by the premises, to replacement problems as related to the original or acquired characteristics of sedimentary hosts. Most of what has been said would apply equally well to deposits in igneous rocks of layered character, such as tuffs or lava flows. The zinc-copper deposits of Buchans, Newfoundland, the pyritic copper-gold-zinc deposits in the layered lavas, etc., of the Noranda district, Quebec, and the copper deposits of the amygdaloid lavas of Michigan are good examples. For all these bedded epigenetic deposits, igneous and sedimentary, many useful empirical facts have been accumulated; some general principles of wide application are apparent; but acceptable explanations of many important features and principles of replacement are still to be formulated.

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CHAPTER 30

GEOCHEMICAL PROSPECTING FOR ORES *

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Geochemical methods of prospecting are based on the premise that a chemical pattern exists in relatively accessible natural material that can be used as a guide in locating relatively inaccessible deposits of valuable minerals. Such chemical patterns are most commonly the result of the dispersion of elements and compounds from the site of primary deposition of the ore, and they assume shapes controlled by the characteristics of the agents of dispersion and the structure and composition of the material through which the dispersion takes place.

In petroleum exploration, most methods classified as "geochemical" depend on analysis of soils, soil moisture, or soil air for hydrocarbons or radioactive elements derived by diffusion from the underlying oil pool. This subject has been discussed at length in the literature of petroleum exploration (Rosaire, 1939; Sokolov, 1947; see also entries under Geochemical Prospecting in the Geophysical Abstract series of the U. S. Geological Survey and U. S. Bureau of Mines).

In work on ore deposits, two distinct varieties of dispersion patterns have been reported: primary or "genetic" patterns, formed by hydrothermal or magmatic processes related more or less directly to the ore-forming process itself; and secondary patterns resulting from the decomposition and scattering of ore material by present-day weathering processes.

Genetic dispersion patterns include the distribution of minerals and elements in the wall rock, alteration zones, and barren vein systems deposited by the mineralizing fluids responsible for the introduction of the ore. The problem is so closely related to the primary ore-forming process that it can be most effectively studied as an integral part of the general geologic setting of the deposits. The general aspects of genetic dispersion patterns have been discussed by Sergeev (1941,

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p. 22), and examples have been described by Riley (1936), Newhouse (1941, p. 144), and Lovering, Sokoloff, and Morris (1948).

This chapter presents a review of methods of prospecting based on systematic exploration for secondary dispersion patterns by chemical analysis of soils, vegetation, and water. The dominant trend in the zone of weathering is a scattering of the primary ore materials, as contrasted with the dominantly concentrating effect of ore-forming processes. Physical forces tend to break up the original minerals at the same time as chemical agencies oxidize or otherwise modify the primary minerals. Some of the weathering products are relatively insoluble in water and tend to remain in the gossan or residual soil near their source in the parent rock. Other material may be more soluble and will be dispersed in ground and surface waters. This simple picture is modified, however, by mechanical erosion and fluvial or glacial transport of the insoluble residual materials, on the one hand, and by immobilization of the water-soluble fraction by subsequent reprecipitation, on the other.

Effective prospecting based on studies of weathering products is possible only where a diagnostic variation in the chemical composition of residual soils, glacial tills, alluvium, vegetation, or natural water exists and can be readily detected and interpreted in terms of an undiscovered deposit of valuable minerals. It requires an integration of the principles and techniques of chemistry with specialized studies of the local geology, processes of weathering and soil formation, glaciology, sedimentation, botany, and hydrology. In spite of the apparent complexity of the problem, considerable progress has been made in the past 15 years both in understanding the basic principles and in applying chemical techniques to practical exploration problems.

The following review of the subject is an attempt to summarize in integrated form the results of more or less independent work on geochemical prospecting in Scandinavia, Russia, Canada, and the United States during the past 15 years, together with pertinent related data from the recent work of geologists, chemists, soil scientists, and botanists. Except for a few very brief articles (Lundberg, 1940a, b, 1941; Sokoloff, 1948), earlier summaries have dealt specifically with work in Scandinavia (Landergren, 1939; Hedström and Nordström, 1945; Rankama, 1941, 1947) and in Russia (Flerov, 1938; Ozerov, 1937; Sofronov and Sergeev, 1936; Sergeev, 1941; Sofronov, 1936; Zaidina and Sergeev, 1938). The summary by Sergeev (1941) includes a discussion of general principles as well as a review of direct practical applications and is by far the most comprehensive treatement of the subject to date. Thyssen (1942) has published a useful summary of the basic principles to be considered in vegetation sampling as a prospecting method.

DISPERSION PATTERNS

Sampling campaigns in geochemical prospecting work should be planned with due regard for the geometry of the dispersion pattern. The characteristic dispersion pattern of an element under given conditions depends on both the mechanics of the dispersion process and the chemical equilibrium of that element with its environment. Many of these factors are only very poorly understood, and much more research will be necessary before it is possible to evaluate them properly.

Dispersion patterns in the zone of weathering may be conveniently grouped according to their characteristic form, following a modified form of the system of classification set up by Sergeev (1941):

Residual and vestigial weathering products. A variable proportion of the weathering products of an ore deposit may remain in the gossan or residual soil directly over or very near their source in the bedrock. "Residual" elements remain behind in relatively large proportions compared with their concentration in the parent material, whereas "vestigial" elements are present only in very minor though still detectable quantities, the remainder having been removed in solution.

Dispersion halos. The diagnostic ore elements have migrated laterally from the ore body to form a more or less symmetrical distribution pattern or "halo" (Russian "oreol") in soil or vegetation.

Dispersion fans. Glacial action scatters the erosion products of an ore deposit in the form of a fan opening out in the direction of ice movement and converging toward the source. It is probable that soluble material moving in the ground water also assumes a similar form, where the fan opens out in a direction down the slope of the water table.

Dispersion trains. Where the weathering products of an ore deposit enter the surface drainage as dissolved salts or water-borne sediment, their distribution takes the form of a "train" (Russian "potok") controlled by the linear drainage pattern of the stream.

The three principal agents of dispersion are air or other gas, glacial ice, and water. Gaseous dispersion is important in geochemical prospecting for petroleum, but at the present time it is of little more than academic interest in ore prospecting. Glacial and aqueous dispersion, however, have an immediate bearing on our present problems and deserve special consideration.

Glacial Dispersion

Glacial erosion and transport is predominantly a physical process. The preglacial soil and weathering products, together with a variable amount of material plucked from the unweathered rock, are moved physically in the direction of the ice movement. Under ideal conditions the material removed from a given locality will be deposited in the ground moraine in a fan-shaped pattern converging toward the locality where the material originated. The relative abundance of such material in the till will fall off rapidly with distance from the source. This, of course, presupposes the absence of multiple ice movements in several different directions and excessive complication by glaciofluvial action.

Studies of the distribution of glacial boulders of distinctive rock types illustrate the characteristic fan-shaped distribution pattern (Goldthwait, 1925; Lundqvist, 1935) and show that most of the morainal material is of relatively local origin (Salisbury, 1900; Alden, 1918). Following these principles, Scandinavian investigators have used systematic mapping of ore boulders as a method of locating deposits buried beneath the glacial cover (Sauramo, 1924; Sederholm, 1922; Ödman, 1947), and in Sweden, particularly, "boulder hunting" has become a standard method of prospecting in both governmental and private organizations.

The same problem may be attacked by chemical rather than mineralogical methods, by analyzing the fine-grained fraction of the till. A single relatively small sample of the fines may contain many particles of ore material that will be indicated in the chemical analysis, whereas many thousands of barren boulders must be laboriously examined for every ore boulder that is found and mapped. The difference in the two approaches is thus primarily one of scale.

A chemical survey of the distribution of copper, lead, and zinc in organic surface soil derived from till near the Lossius deposit in the Røros district of Norway showed relatively high metal concentrations (Cu 100+, Pb 20+, and Zn 1,000+ parts per million) for a distance of 250 meters from the ore, measured in the direction of ice movement (Vogt and Bergh, 1946, 1947). A preliminary study by the U. S. Geological Survey of the zinc content of till in the vicinity of the Hyatt zinc mine, St. Lawrence County, New York, showed high concentrations (over 300 parts per million compared with background of less than 100 parts per million) in the surface till 800 feet to the "lee" of the ore. These are the only investigations of the method to date, and much more work will be necessary before we can say that the chemical approach to glacial prospecting will have general applicability.

Aqueous Dispersion—Mobility

Water plays the dominant role in the dispersion of weathering products in unglaciated terranes. It is not only the medium in which most of the chemical changes in the zone of weathering take place, but is also the agency primarily responsible for the removal of weathering products, both soluble and insoluble, from the place of their origin.

In the weathering cycle, each individual element is exposed to a different series of physical, chemical, and biological reactions between the time it first comes under the influence of weathering agents until it reaches its ultimate site of resedimentation. Although in detail, the individual reaction may be both complex and obscure, yet the summation of the reactions may be determined empirically by observing the rate at which a given element tends to move from its source in parent rock. This rate of movement has been referred to as "mobility" in the cycle of weathering (Polynov, 1937, p. 162; Reiche, 1945, pp. 42–45; Smyth, 1913). Elements that tend to remain in gossans and residual soils near their source in the parent rock are said to have a low mobility, whereas those that tend to move out in suspension or solution in ground and surface waters and in the circulatory systems of vegetation are said to have a high mobility.

The initial factor that affects the mobility of an element is the stability of its primary minerals in the zone of weathering. Thus gold, platinum, tin in cassiterite, tungsten in wolframite, and chromium in chromite will tend to have a low mobility, whereas metals in the relatively unstable sulphide minerals will tend to have a correspondingly high mobility.

After the components of the primary mineral have gone into solution, the dominant factor governing mobility is the *p*H of the water in which the elements are dissolved. As the *p*H of a dilute aqueous solution of a metal is raised, a point is reached at which that metal starts to precipitate as hydroxide or basic salt. Table 1 shows the *p*H of hydrolysis of a few common metals.

Inasmuch as ground and surface waters in normal temperate climates commonly have a *p*H of 5.5 or higher, it will be readily seen that iron, aluminum, and copper will tend to be relatively immobile. Experimental studies of the copper content of natural waters in which the *p*H exceeds 5.5 show that it is saturated at very low concentrations, re-

TABLE 1

*p*H OF PRECIPITATION OF HYDROXIDE OR BASIC SALT FROM DILUTE SOLUTIONS
(Britton, 1942, p. 79)

Silver	7.5–8.0	Ferrous	5.5
Zinc	7.0	Cupric	5.3
Cobalt	6.8	Aluminum	4.1
Nickel	6.7	Stannous	2
Lead	6.0	Ferric	2

gardless of the richness of the source of copper (Leach, 1947; Lovering, Huff, and Almond, in preparation). A similar reaction takes place in soils, where a high *p*H tends to reduce the mobility of zinc, copper, and some other ore metals (Peech, 1941).

Soluble material present in solution under some conditions has an important effect on the mobility of a given element. Some anions form slightly soluble compounds, such as silver chloride or lead sulphate, and their presence reduces the mobility of those metals. Some anions form soluble complex ions with certain metals and consequently tend to increase the mobility of those metals. Furthermore, precipitation of minerals such as manganese and iron hydrates tends to "scavenge" many metallic ions and remove them from solution (Goldschmidt and Peters, 1934; Goldschmidt and Hefter, 1934; Forrester, 1942; Vogt, 1942c; Landergren, 1948, p. 135).

Cation exchange with organic or inorganic colloidal matter tends to modify the mobility (Burd, 1947; Antipov-Karataev, 1947; Noll, 1931). Organic matter tends to remove certain metallic ions from solution, although the exact mechanism is not well understood (Hibbard, 1940; Lucas, 1948; Bremner *et al.,* 1946; Hasler, 1943; Fischer, 1937). There is also a selective action by growing organisms, some of which can take up certain elements and reject others, depending on their metabolic requirements (Goldschmidt, 1937; Robinson and Edgington, 1945; Thyssen, 1942; Lovering, 1927; Riley, 1939). The oxidation potential of the environment may influence the mobility of elements having two or more common valence states (Chapman and Schweitzer, 1947; Murata, 1939).

Mobility is thus not a simple thing. However, if we are to deal intelligently with problems involving dispersion in the cycle of weathering, it is a subject that we must explore further and understand more fully.

DIRECT BOTANICAL INDICATIONS

Under certain conditions, plants respond in a specific and diagnostic manner to variations in soil composition. Certain species known as "indicator" plants (Beath *et al.*, 1939) grow only on soil containing large concentrations of a particular element. In Germany it is reported that a variety of violet grows only on zinc-rich soil (Jensch, 1894) and has been useful in locating zinc ore in the underlying bedrock. Indicator plants have been mentioned for many other metals and minerals (Dorn, 1937; Lidgey, 1897; Thyssen, 1942; Rickard, 1926; White, 1929; Monigatti *et al.*, 1947), though it is difficult to confirm some of the reported observations.

More frequently, the effect of high concentrations of certain metals in the soil is to modify the entire plant assemblage (Vogt, 1942a, b). For example, the plant ecology over the outcrops of the San Manuel copper deposit in Arizona, where the copper content of the soil is very high, is quite different from that on the adjoining normal soil (Lovering, Huff, and Almond, in preparation). A more commonly observed phenomenon is the relative infertility of soils either because of their acidity or their metal content (Robinson, Edgington, and Byers, 1935; Bateman, 1930; Guillemain, 1913; Vogt and Braadlie, 1942; Bell, 1931).

Another botanical indication of metals is the development of characteristic plant symptoms due to deficiencies or excesses of metals in the soil. Agricultural scientists have been particularly concerned with mineral deficiencies not only of major mineral constituents but also of many elements normally present in the soil only in very small quantities. Insufficient copper, zinc, molybdenum, boron, and cobalt in the soil may cause serious deficiency diseases either in the vegetation or in the animals feeding on that vegetation (Brenchley, 1947; see also references listed in Willis, 1948). Toxicity symptoms in plants and animals due to excesses of certain elements such as zinc, copper, cobalt, and nickel have also been reported (Brenchley, 1927; Robinson and Edgington, 1948; Jensch, 1894; Vogt and Bugge, 1943; Piper, 1942; Staker, 1942; Bergh, 1948; Hewitt, 1948; Millikan, 1948). Under favorable conditions, systematic searching for such diagnostic plant symptoms may be useful in prospecting.

Such direct botanical indications of ore are especially worth investigating as they offer a reconnaissance method of scouting without the immediate necessity of careful sampling and chemical analysis.

SAMPLING FOR CHEMICAL ANALYSIS

The delineation of a geochemical indication of ore in any type of surface material involves a contrast between the anomalous metal concentrations on one hand and the normal or background concentrations on the other. The background varies widely from one locality to another with local geology, climate, drainage conditions, and many other factors and can best be determined separately for each project. For general reference, however, the literature contains useful compilations of the average metal content of rocks (Goldschmidt, 1937), living organisms (Vinogradov, 1935), and surface water (Braidech and Emery, 1935). No comprehensive estimate of the average composition of soils has been made, although abundant data have been gathered on individual elements (Holmes, 1943; Mitchell, 1944; Siniakova, 1945; Jacks and Scherbatoff, 1940; Maliuga, 1944; Robinson, 1914; Slater *et al.*, 1937).

Gossans. Information on the mineralogy and grade of underlying sulphide ore can under some conditions be gained from mineralogical studies of surface material (Locke, 1926; Blanchard, 1930, 1931, 1942; Blanchard and Boswell, 1925, 1934, 1935; Boswell and Blanchard, 1927, 1929). Chemical analysis for traces of ore metals has apparently not been applied to gossan study, and it is impossible to discuss sampling procedures at present.

Soils. The term "soil" as used by agriculturists refers to surface material that has been modified chemically and physically by bacteriological and other organic activity, and that can, as a result, support growing vegetation. It is commonly layered, with an upper "horizon" of leaching (the *A* horizon or topsoil), an intermediate zone of concentration (the *B* horizon or subsoil), and the parent material (the *C* horizon, usually weathered rock, alluvium, or glacial material). Depending on local conditions any one of the three soil horizons may give optimum results in sampling for metals. Some metals are taken up in solution through the circulatory system of trees, where they are concentrated in the leaves; when the leaves fall to the ground and rot, the metals remain near the surface in the organic part of the *A* horizon (Goldschmidt, 1937; Vogt and Bergh, 1946, 1947; Sokoloff, 1948). In the absence of forest trees, the metals may be leached from the topsoil, and it becomes necessary to collect deeper samples from the *B* or *C* horizon in the soil (Hawkes and Lakin, 1949; Sergeev, 1941, Fig. 8). Each problem should be treated as a special case, with a preliminary investigation of the optimum depth of sampling before the routine work is started. The optimum size of sample and the mechanical fraction containing the most diagnostic variation in metal content should also be determined by preliminary experiments for each field problem.

Alkaline soils tend to be richer in copper and zinc than acid soils (Holmes, 1943), whereas the reverse is apparently true for molybdenum (Lewis, 1933). Thus in areas where the soil acidity varies from place to place it may be desirable to determine the *p*H of each sample of soil as an aid in interpreting the data. No serious interference has been reported from artificial contamination of soils if normal care is taken in obtaining clean samples. In the east Tennessee zinc district where the fields have been limed with zinc tailings from the concentrating plants, no noticeable effect was observed (Hawkes and Lakin, 1949).

Where the soil is free of rocks, a hand-operated soil auger is satisfactory for sampling for depths up to 20 feet. For rocky soils a hole may be driven with a crow bar, and the sample collected with a spoon attached to the end of a pole (Sergeev, 1941, Fig. 18). For large-scale surveys, power-driven equipment will probably be desirable. Surface soils, of course, can be sampled with no special equipment.

Alluvium. In sampling alluvium, the same principles may be followed as in alluvial prospecting for heavy minerals (Raeburn and Milner, 1927). Under certain conditions experience has shown that sieving the samples and rejecting all but the fines materially reduces the number of erratic and inconsistent data (Lovering, Huff, and Almond, in preparation).

Till. Any sampling of glacial material should be done with due regard for the glacial history of the area and the resulting structure of the glacial deposits. In general, the same precautions should be taken in till sampling as in soil and alluvium sampling, except that sieving of the sample may be a more critical factor, especially with subaqueous tills that have been diluted with a variable amount of sand.

Vegetation. In sampling and analysis of plants as a prospecting method, it should be borne in mind that the metal content of the plant parts cannot give a better picture of the metallic dispersion pattern than the metal content of the nutrient solution available to the root system. The life processes of the plant may further modify the relative concentrations of the various inorganic constituents of its structure (Thyssen, 1942). The outstanding point in favor of the method is that the root system of a large plant or tree draws its moisture from a large volume of inaccessible soil or underlying rock and concentrates the contained mineral matter in the leaves, where it can be more readily sampled.

The uptake of a given element by a growing plant depends on the availability of that element in the nutrient solution rather than on the total concentration in the soil. The ratio of available to total element in a soil is primarily a function of the *p*H, organic content, and colloid content of that soil (Jacks and Scherbatoff, 1940; Erkama, 1947). Many plants have a selective action whereby they can take up certain elements and reject others (Thyssen, 1942); furthermore, those that are absorbed may be concentrated in different parts of the plant, depending in part at least on the circulatory pattern and nutritive requirements of the plant (Rottova, 1947). The reaction varies from one species to another, and with time of year (McHargue and Roy, 1932; Piper and Walkley, 1943). In general it is found that zinc and copper tend to be concentrated in the leaves, twigs, and growing buds (Warren and Howatson, 1947), whereas lead is commonly precipitated in the root cells (Hammett, 1928). The zinc content of plants varies widely, depending on the species of plant and the available zinc in the soil (Robinson, Lakin, and Reichen, 1947), whereas the range for copper is generally much less (Erkama, 1947). Species of plants that can concentrate relatively large proportions of an element in their living parts are known as "accumulator" plants (Robinson and Edgington, 1945). Of the woody plants, willows, aspens, birch, hickory, and pine have been cited as outstanding accumulator plants (Rankama, 1940; Robinson and Edgington, 1945; Robinson, Lakin, and Reichen, 1947; Thyssen, 1942; Warren and Howatson, 1947; Vogt, Braadlie, and Bergh, 1943; Vogt and Bugge, 1943; Warren and Delavault, 1948; Maliuga, 1947). Accumulator plants are generally regarded as most likely to give good results in prospecting. However, the possibility remains that the variation in metal content of a species that does not ordinarily concentrate large amounts of that metal may give a more accurate reflection of the total metal content of the soil. In systematic sampling, it is essential that comparisons be made only with data from the same parts of identical species of plants or trees, preferably all sampled at the same time of year. Successful results have been reported by analyzing twigs for both copper and zinc and using the ratio in interpretation rather than the absolute values. Thus an abnormally high Cu:Zn ratio indicates copper in the soil, and a low ratio indicates zinc (Warren and Delavault, 1948).

In collecting plant tops, care should be taken to avoid contamination of the sample with soil. Tree leaves are relatively free of contamination of this kind. In industrial areas where there are factories or smelters, the plants and trees may become so contaminated with metals from the air that no significant data can be obtained (Dunn and Bloxam, 1932).

Leaf samples may be collected either by simply picking whole leaves from different parts of one or more trees, or by cutting small discs of standard area from the leaves with a device similar to an ordinary paper punch (Reichen and Lakin, 1949).

Water. Sampling of stream water as a prospecting method is identical in principle to alluvial prospecting; in both, the trail of increasing concentrations of some material derived from a bedrock ore is followed upstream to the source. Following the precedent set by alluvial prospectors, Sergeev (1946) has described a sampling pattern for stream waters wherein samples are collected in groups of three near the mouth of each tributary to the main stream. One sample is taken from the main stream above the junction, one sample downstream from the junction, and one from the tributary itself. Such data may be plotted either on graphs or directly on a map (Sokoloff, 1948; Huff, 1948) to show the source of any unusual amount of metal present in soluble form.

Sampling of ground water is limited, of course, by the distribution of wells and springs where samples can be collected, and it constitutes a special problem that must be separately evaluated for each field project.

Work by the U. S. Geological Survey in the southwestern Wisconsin zinc district has shown that zinc ore below the permanent water table does not discharge sufficient metal into the ground water to give an indication of its presence. When the ore is at or above the water table, however, the associated ground water has a significant high zinc content, of the order of 0.4 part per million, as compared with a background of less than 0.1 part per million. To date, the most successful results with water sampling have been obtained with zinc, though experiments with sulphate show some promise (Vogt, 1939), and under some conditions copper in stream water appears to be indicative of copper ore (Vogt and Rosenqvist, 1942). Studies by the U. S. Geological Survey, however, indicate that the copper content of natural water cannot generally be used as a prospecting guide.

Natural water is outstandingly susceptible to contamination. It is extremely difficult, and many times impossible, to obtain water from a well that is not hopelessly contaminated with zinc and copper from the plumbing. Stream water, except in wilderness areas, may be seriously contaminated from metals in sewage and rubbish heaps, discharge from factories, mine dumps, and abandoned mines. Spring water, however, is commonly free of artificial contamination.

ANALYTICAL PROCEDURES

Most geochemical methods of mineral exploration depend on chemical analysis of soil, vegetation, or water for traces of ore metals. Because of the large volume of samples that must be tested to obtain a working picture of the dispersion patterns of metals, the analytical methods should be both rapid and inexpensive. In addition to these requirements, a method that can be applied either directly in the field or in local field headquarters is desirable in that the prospector can know immediately whether or not he is on the trail of a hidden deposit and thus can plan his sample collecting more effectively. The speed and economy of the test are more critical than accuracy, as in most problems the contrast in metal content indicative of ore is in excess of several hundred percent.

To date the most successful methods have been spectrographic and colorimetric analysis and spot tests.

Spectrographic analysis. Spectrographic analysis has been used most extensively in geochemical prospecting work in Russia and Sweden. Physicists of the Central Geological and Prospecting Institute of the Soviet Union have developed spectrographic equipment suitable for use either in the laboratory or under field conditions (Ratsbaum, 1939). The field instrument can be dismounted and transported with its mobile power supply by truck or, if necessary, on pack animals. Under ideal operating conditions it is claimed that close to 1,000 soil analyses per day can be made by one crew (A. P. Solovov, personal communication). However, Sergeev (1941, p. 45) states that under normal working conditions 140 spectrograms on the stationary model or 100 on the field model can be prepared per day by a three-man crew, exclusive of time required for sample preparation. This equipment has been most successful with analyses of soil material for tin, tungsten, lead, nickel, arsenic, antimony, and molybdenum (Safronov and Sergeev, 1936; Sergeev, 1941, pp. 30–40; Tikhomirov and Miller, 1946). Estimations are made by visual comparison with standard spectrograms. Maximum sensitivity is said to be 0.01 percent for tin, lead, nickel, arsenic, and antimony, and 0.05 percent for tungsten.

In Sweden, stationary spectrographic equipment capable of high productivity was developed by S. Palmqvist and N. Brundin, of the Swedish Prospecting Company, in 1936. This instrument was designed for analysis of ashed plant material and with a four-man crew could turn out 400 determinations per day. Most success was obtained with tin and tungsten, though some work was also done with lead, zinc, chromium, molybdenum, copper, and silver (Svenska Prospekterings Aktiebolaget, 1939; Hedström and Nordström, 1945, pp. 6–9).

The advantages of the spectrographic method for geochemical prospecting are its speed and the fact that many elements can be determined in a sample with little more work than it takes to determine one. The disadvantages are the initial cost of equipment, difficult portability, need for skilled operator, and lack of sensitivity for some important elements, notably zinc.

Colorimetric analysis. Colorimetric methods of analysis have had wide application for some time in determining traces of metals in organic and inorganic materials (Sandell, 1944). Such methods are based on the conversion of the metal to be determined into a substance whose solution (or suspension) is strongly colored.

Colorimetric analysis was first applied to geochemical prospecting on a large scale by the U. S. Geological Survey (Lovering, Sokoloff, and Morris, 1948; Huff, 1948; Lakin *et al.*, 1949; Reichen and Lakin, 1949). A complete analytical kit for determinations of zinc in waters, soils, and vegetation can be packed in an easily portable tool box, which can be replenished when necessary from stock solutions carried by truck. Under normal working conditions in a temporary shelter, one man can run 30 zinc determinations per day. The accuracy is about ± 30 percent, and the sensitivity is adequate to detect and measure the zinc content of all normal samples. The advantages of colorimetric methods are the portability, low initial cost, ease of operation, and sensitivity.

Spot tests. Spot tests were first successfully applied in geochemical prospecting by Soviet geologists (Sergeev, 1941, pp. 40–44). The basic principle is much the same as for colorimetric analysis except that the sensitive reagent is impregnated in filter paper and the estimation made by observing the color of a spot produced by a drop of the solution to be tested (Feigl, 1946). Russian workers report satisfactory results with copper, nickel, cobalt, and silver, with a productivity of 40 samples per element per man-day. Within the last year the U. S. Geological Survey has been conducting developmental work on spot tests for copper and nickel. The advantages and disadvantages of spot tests are much the same as for colorimetric analysis. Outstanding features of spot tests, however, are ease of estimation and the fact that a permanent record is obtained.

Other methods. Other analytical methods that have been tried with varying degrees of success in geochemical prospecting include polarographic analysis (Kolthoff and Lingane, 1941; Sergeev, 1941, p. 44), nephelometry (Sandell, 1944, pp. 69–71), electrode polarization (Sergeev and Solovov, 1937) and microchemical methods (Short, 1940).

NEED FOR FURTHER RESEARCH

In spite of the considerable volume of work that has already been done, both on the principles and on the applications of geochemical methods of prospecting for ores, the field is still in its infancy. Broadly speaking, the aspects of geochemical prospecting that need further research may be listed as follows:

Analytical procedures. New or improved tests are needed for many important elements, such as lead, cobalt, molybdenum, vanadium, arsenic, antimony, silver, and gold.

Geochemical principles. A better understanding is needed of the chemical and biological factors that affect the mobility of ore metals in the cycle or weathering.

Field applications. Many more experimental studies of the dispersion patterns of ore metals emanating from known deposits are necessary before the general applicability of geochemical methods to prospecting can be evaluated.

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Part 6

PETROLEUM GEOLOGY PROBLEMS

Chapter 31

SUBSURFACE TECHNIQUES

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In subsurface studies of oil-bearing formations the geologist is constantly in search of new techniques and combinations of techniques which may be of value in discovering new oil pools or extensions of known accumulations. In the earlier history of oil finding the prime technique consisted in locating structures exposed at the surface. This was accomplished by determining the elevations on a key bed, or various key horizons, exposed on the surface and contouring these numerical values on a map. It was not long before the oil man began to compare the subsurface elevations of key beds in the sequence of strata penetrated in neighboring wells. Many drillers and operators kept penciled notes on the depths to the top of some of the sandstone, shale, and limestone layers and sometimes attempted to describe them. J. F. Carll (1875, pp. 23–31, 35) was the first man to plot and correlate formations logged by the driller into what he termed "vertical sections." Considerable advances have been made since Carll's time in the techniques of logging wells and in the manner of interpreting well logs.

Within the past several decades the geophysicist has developed several techniques for subsurface probing which require neither surface outcrops nor well-log information. He is able to locate deeply buried structures by means of gravimetric, seismic, magnetic, or electric data. By a combination of geological and geophysical methods it is believed that most of the major structures in sedimentary rocks in this country have been mapped. Many of them have been drilled and proved productive, whereas others have been proved barren. Many pools such as the Burbank, Bartlesville, Cheyraha, Wewoka Lake, Southwest Antioch, Elmore, and Katie pools of Oklahoma, the shoe-string sand pools of Kansas, the east Texas pool, and numerous others that are not anticlinal structures, give clear-cut evidence that something more fundamental than closures governs the distribution of oil and gas in these pools. That "something" is sedimentation and stratigraphy.

A sedimentological approach to the problem of locating oil is not predicated on any one factor as a cause of accumulation, and usually it involves numerous techniques. In the past few years the discovery of oil in reefs in such pools as the Leduc (Link, 1949, pp. 381–402) and Redbank of Alberta and the Marine pool (Lowenstam, 1948, pp. 153–188) of Illinois has served to focus the attention of the oil man on the combined techniques of the structural and the sedimentological geologist. The geophysicist has refined his techniques so as to locate reefs that are overlain by arched strata. Where there is little or no reflection of structure above a reef, detailed paleogeographic and facies studies hold out the greatest promise for adequate techniques in finding them in the subsurface.

PRINCIPAL SOURCES OF SUBSURFACE DATA

Well logs are the most important single tool in subsurface stratigraphic analysis. When they are used in conjunction with other types of data, a fairly complete picture can be reconstructed of the rock strata far below the surface of the earth, that is, the types of lithology, their respective thicknesses, structural configuration, and facies relationships. Well logs are of several types, but all have one feature in common in that they are all either direct or indirect records of the various types of strata penetrated by the bit in the drilling of the hole.

The most prevalent types of logs currently in use are illustrated in Fig. 1. All these logs were made from data on the same borehole, and they serve to illustrate the precise nature of the information available to the geologist interested in making subsurface stratigraphic studies. Frequent reference to Fig. 1 will prove useful to a better understanding of the following discussion of different types of logs.

SAMPLE LOGS

In cable-tool drilling, samples may be bailed directly from the bottom of the hole every time an additional 5 to 10 feet of new hole has been made. When drilling in the producing horizon the bailer may be run every foot or two. In all events the rock cuttings dumped from the bailer are quite representative of the formation drilled since the previous run of the bailer. In rotary drilling it is impossible to obtain samples as good as those obtained in holes drilled with cable

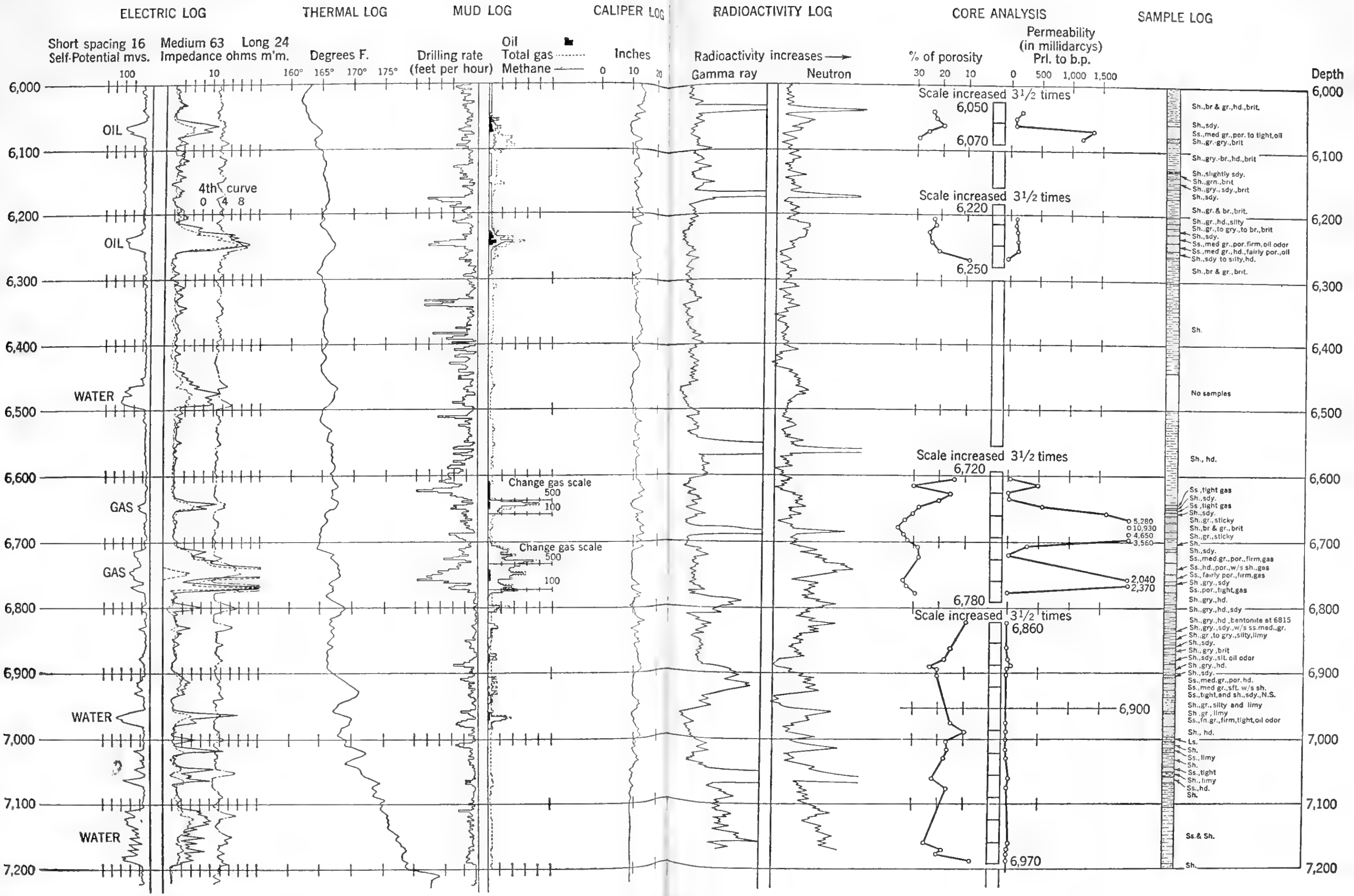

FIG. 1. Methods of logging subsurface strata. An illustration of seven fundamental ways in which subsurface strata can be logged, either in a borehole or from rock materials brought to the surface. Direct comparisons can be made of these logs as they are all records of the same well. (Courtesy of Humble Oil & Refining Company.)

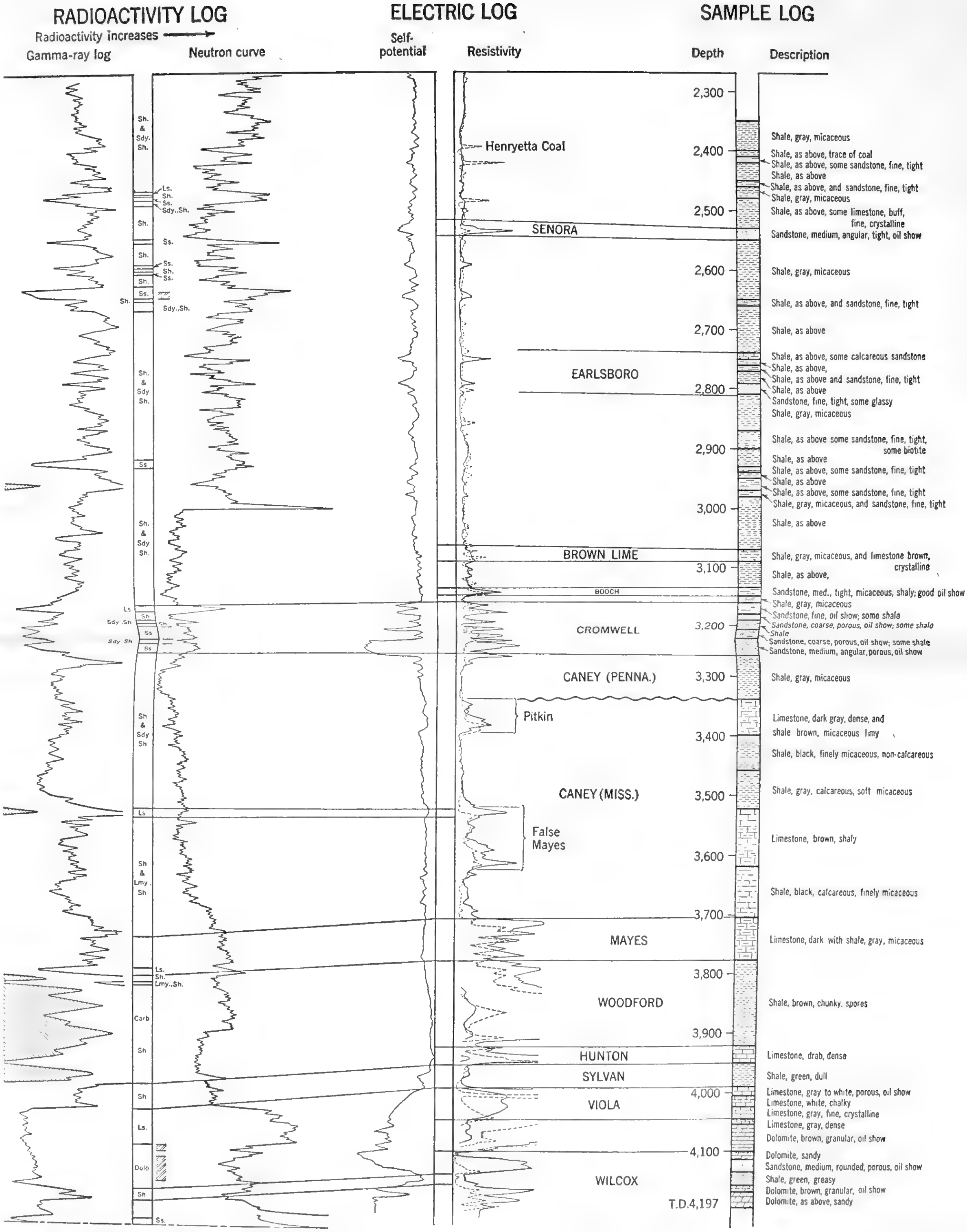

Fig. 2. Comparison of radioactivity, electric, and sample logs of two wells. The electric and sample logs are from the same well, and the radioactivity log is from an offset well 660 feet away. (Courtesy of Blackwell Oil and Gas Co.)

tools. Samples are brought to the surface by means of the mud slurry moving up the hole outside of the drill pipe. Differential settling, scattering of the fines, contamination from the walls, time lag, and finally loss of disaggregated fines in screening at the slush pit may combine to yield a sample that only faintly resembles the formation penetrated. Thin key beds may be missed entirely, or their cuttings may be so spread along the column of returning drilling mud that it is impossible to pick either the top or the bottom.

It is standard practice for the geologist to examine the cuttings, whether they be cable-tool or rotary, with a binocular microscope. He notes the depths of recognizable formations and describes each unit. This information may be kept in notebooks, typed and kept in company files, or plotted on log forms printed especially for this purpose. On these forms, depths and lithologic characteristics of the strata in neighboring wells may be directly compared by laying them side by side.

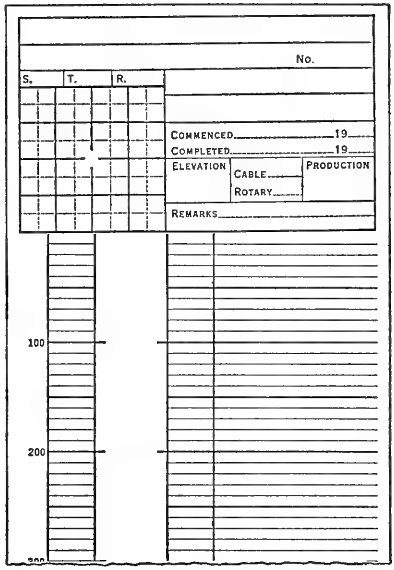

FIG. 3. A type of log form used in plotting sample descriptions. The *S* stands for section; *T* for township; *R* for range, and "No." for well number. The vertical scale on the original form is 1 inch = 100 feet. (Courtesy of Mid-West Printing Co.)

Written records of the formations penetrated, when plotted graphically to scale, are known as strip logs. Such logs are customarily plotted on strips of heavy paper or lightweight cardboard, and the different types of rock are indicated by means of standardized symbols or colors. Color symbols usually are employed by the geologist with yellow representing conglomerate, gravel, sandstone, or sand. Gray shale, slate, and clay may be left blank; red shale, slate, or clay, red; limestone, dolomite, and chalk, blue; coal, black. Special features of these different types of rock may be indicated by descriptions in the blank spaces to the right of the color symbols. These features may include principal lithologies with percentage of each color, texture, angularity of grains, index fossils, nature and amount of cementing material, estimates and nature of porosity, presence of secondary crystallization, and frosting of sand grains. Such descriptive features of the formations penetrated are indicated on the sample log in Fig. 2.

Such graphic records, when laid side by side, serve as an excellent means of identifying formations and key horizons, of noting changes in type of rock, changes of thickness of intervals, etc. Printed log forms for the noting of pertinent data are of many types. The top portion of a typical log form is shown in Fig. 3. A convenient and customary vertical scale is 100 feet to 1 inch. Such log forms may be purchased with graduated depths of 4,000 feet and 6,000 feet.

ELECTRIC LOGS

Electric logging has become the most universal method of logging oil and gas wells, principally because of its rapidity, accuracy with respect to depth, facility in correlation work, and relatively low cost. The use of electric logs has to some extent supplanted the examination of cuttings and cores. Although they have definite and severe limitations, electrical logs are probably the most important and useful tool available in subsurface geological investigations.

Conrad and Marcel Schlumberger, French geophysicists, discovered that in a borehole the electrical potential, with respect to a fixed reference, is different opposite a bed of shale from that opposite a bed of sandstone, and they developed a technique for recording these differences. They also adopted the methods for determining earth resistivity to use in a borehole. Their technique for electrical logging was used in Russia, Romania, and Venezuela before 1930 but did not come into general use in the United States until 1935. A typical electric log is shown in Fig. 2.

The potential curve, also called self-potential, spontaneous potential, or S.P. curve, is a curve of natural electrical potential in the hole plotted against depth. It is always recorded on the left-hand side of the log strip, with depth increasing downward and positive potential increasing from left to right. It is obtained by measuring the difference in direct-current potential between a grounded electrode placed near the wellhead at the surface and that of another that is lowered slowly on a cable into the well. The record customarily is made by a recording galvanometer on photographic film that is driven by a geared coupling attached to the sheave over which the cable passes at the wellhead. By changing the gears the film can be made to travel 1 inch for each 20, 50, or 100 feet of movement of the traveling electrode. The changes in potential difference range from 1 to 250 millivolts, and they appear as "kicks" on the curve. In general, sandstones are negative with respect to shale.

The causes of the potential differences are still somewhat obscure, but they appear to represent the algebraic sum of several types of electrical potential due to the physicochemical behavior of the drilling fluid and the connate fluids. They probably are the result of the combined effects of: (1) the potential that is developed at the interface between a concentrated salt solution (the connate water in the rock) and a dilute solution (the drilling fluid); (2) the potential that results from "cataphoresis" when an electrolyte flows through a porous medium as a result of a difference in pressure between the drilling mud and that of the fluids in the formation; and (3) a potential difference that develops across the interfaces when clay and sand, both saturated with salt water, come into contact with fresh water. The relative importance of the three effects is not known, and the physical chemistry of the third source is not fully understood. In general, subsurface sands have a low (high negative) potential with respect to shale, although fresh-water sands, generally near the surface, have a positive potential. The potential of limestones may be very low, intermediate, or high.

There is a partial relationship between the magnitude of the cataphoresis effect, or flowing potential, and the permeability. However, the principal factor that affects the potential curve is the amount of clay in the rock; the less the clay, the more negative the potential. The amount of clay also affects the permeability; thus the cataphoresis effect, amount of clay, and permeability are all interrelated factors.

The resistivity log (or logs) is plotted on the right-hand side of the strip with the amount of resistivity increasing to the right, as shown in Fig. 2. In actual field practice a resistivity log is obtained by lowering a system of electrodes into a well by means of an insulated multiconductor cable. A voltage source (alternating current or commutated direct current) is applied to one electrode at the surface. This current passes down one of the conductor cables through another current electrode traveling in the hole. A portion of the electrical field established around the current electrode in the hole is picked up by two other traveling electrodes spaced at successively higher intervals up the hole. The supporting conductor cables, by which the two upper electrodes are suspended, are connected at the surface to a potential recorder (voltmeter) between these two electrodes. The difference in potential between them is a measure of the apparent resistivity of the rock formation in the neighborhood of the electrodes. Water in the drilling mud nearly always invades the permeable sands, and, as this water is generally fresh, any sand is likely to have a high resistivity near the borehole. If the three electrodes in the hole are closely spaced, the resistivity might be measured within a zone smaller than the depth of penetration of water filtrate from the drilling mud. The resultant resistivity curve would be that of the drilling fluid plus any dilution effects of the connate water of the surrounding strata. This effect is partially corrected by making additional resistivity runs with the suspended electrodes more widely spaced. In this way the radius of investigation of the electrical field is greater than the depth of penetration of the drilling fluid.

The resistivity curves obtained by additional runs commonly are referred to as third and fourth curves. These curves are measures of resistivity of larger intervals of rock than the second curve, and, although they more accurately portray the electrolytic character of the original fluids in the formation, they are less precise indicators of the tops and bottoms of the various strata. Three resistivity curves (second, third, and fourth curves) are illustrated on the electric log of Fig. 1. It is more customary, however, to use only two such curves, as shown on the electric log of Fig. 2.

In general, shales have fairly low resistivity because of the salt water contained in their pores. Salt-water sands of high porosity have still lower resistivity. Oil and gas sands generally have higher resistivity than shales, depending on the amount of connate water they contain. Limestones generally have high resistivity. Very dense sands also have high resistivity, as do fresh-water sands.

It was believed at first that the resistivity log would indicate whether the permeable beds contained oil or water. Unfortunately they do not. The true resistivity of the rock cannot be determined because of the mud-filtrate invasion, and because the presence of the borehole and the finite thickness of the beds introduce variable correction factors that can seldom be evaluated. Some oil sands contain so much connate water that they show low resistivity.

Accordingly, electric logs cannot be used to estimate either permeability, porosity, or fluid content of subsurface formations. However, changes in lithologic properties of rocks are nearly always accompanied by changes in electrical properties. Thus all the major, and many of the minor, lithologic variations in the rocks exposed in a borehole are shown as shifts in the electric-log curves. It is usually easy to distinguish sand from shale, even though not much can be told about the physical properties of either. Limestones are generally also recognizable. The depths to the lithologic changes are determined to within a few feet, and the thicknesses of individual beds can be determined with similar accuracy. A formation will exhibit a characteristic pattern that is usually recognizable in other wells. As a result, electric logs are extremely useful for correlation, especially for distances up to 5 or 10 miles. They are simpler and more accurate than sample logs for these short distances. Over longer distances the minor lithologic changes are less easily recognized, and such features as rock color and texture and fossils are necessary.

RADIOACTIVITY LOGS

All rocks display varying degrees of radioactivity which are due to the presence of one or more unstable mineral components. Radium, uranium, actinium, and thorium are the radioactive elements of such unstable minerals which are continually disintegrating and forming other minerals of slightly lower molecular weight which in themselves are radioactive. Igneous rocks are the source of all other types of rocks, and radioactive minerals are present in very minute amounts in both this primary source and the metamorphic and sedimentary derivatives. Thus radioactive minerals occur in rocks of all ages and types. Radioactive minerals are more concentrated in some types of sedimentary rocks than in others. In general, shales and clays are more radioactive than sandstones, and "the average radioactivity of limestones is less than that of sandstones" (Bell *et al.*, 1940, pp. 1539–1540). Russell (1941, p. 1769) has observed, "that pure sandstones and limestones almost invariably show less radioactivity than the shales." Coal, salt, anhydrite, and other salines also are weakly radioactive.

In radioactivity logging, the differences in the degree of radioactivity of these different types of sedimentary rocks afford a basis for identifying the different formations. Such differences are well illustrated on the radioactivity log of Fig. 2. An instrument has been devised which is sensitive to radioactive gamma-ray radiation. It consists of a steel cylinder, closed at both ends, containing high-molecular-weight gas. The cylinder is fitted with insulated electrodes which are connected with an external source of direct current. There is an amplifier in the upper part of the instrument, as well as batteries which supply the current to the ionization chamber. As the ionization chamber traverses the hole, gamma-ray emanations from the surrounding strata permit current to flow through the gas between the electrodes of the ionization chamber. The amount of current is directly proportional to the intensity of radioactive emanation from the surrounding stratum.

The ionization chamber is suspended on a cable which transmits the electrical impulses to the surface, where they are further amplified and their magnitude is graphically recorded. A gamma-ray log is illustrated along the left side of the radioactivity log of Fig. 2.

Neutron logging is still another method of recording the formations exposed in a well bore. Such a log is illustrated along the right side of the radioactivity log of Fig. 2. In this method a stream of neutron particles bombards the formations in the well and causes the emission of gamma rays by the hydrogen atoms in the pore liquids. The magnitude of the emitted gamma rays is measured with the aid of an ionization chamber as described above and is dependent, to a large extent, on the fluid content of the formation being bombarded. A mixture of radium and beryllium is the radioactive material responsible for the atomic dissociation and the generation of a stream of neutron particles.

A unique feature of radioactivity logs is that they may be taken through several strings of casing surrounded by cement. Thus they are of considerable value in determining the positions of cased-off sands in old wells. Many old wells were drilled without accurate logs having been kept, and this method of logging is especially adaptable in such cases.

DRILLING-TIME LOGS

A drilling-time log is a graphic picture of the variable amount of time (minutes per foot of new hole) required to drill through the different types of rock encountered. Commercial instruments have been devised with which this type of information is automatically recorded as the drilling of the hole progresses. A drilling-time graph is shown on the left side of the mud log, illustrated in Fig. 1. A short bar indicates a rapid rate of drilling, and a long bar a slow rate. Such a log, when checked against sample cuttings or an electric log, may be of considerable help in the determination of top and bottom of a stratum or in detecting the most porous and soft portions of a sandstone. The rate of drilling is dependent on numerous factors, chief of which are the lithologic character of the rock, weight of the drill stem at the bottom of the hole, rate of rotation of the bit, design and extent of wear on the bit, rate of circulation of the drilling fluid, and the ability of the driller to know the optimum rate of "feeding" the drill. The factors that affect the hardness of a formation are mineral composition, degree of cementation, and nature of cement, porosity, and so on.

CONTINUOUS INSTRUMENTAL LOGGING

Continuous instrumental logging combines several logging techniques in one unit. Such data as depth, thickness, and fluid content of porous formations penetrated by the bit are automatically and continuously logged by this method, as shown in Fig. 4. In the process of drilling through a porous formation the drilling fluid tends to become slightly diluted by any formation fluid (whether water, oil, or gas) liberated. These formation fluids are not only entrained by the drilling mud but are also retained on or in the cuttings circulated to the surface. By continuously testing the drilling fluid and cuttings at the surface, the presence of oil or gas can be detected and the depth of origin determined.

In testing the mud for gas, a motor-driven vacuum pump pulls air through a trap attached to the flow line of the drilling fluid. From the trap it is conveyed to the portable laboratory by means of a flexible hose and passed through a filter, a humidifier, a flow meter, and a "hot-wire" gas-detector instrument where the percentage of combustible gas is determined. This total gas determination gives the percentage of all the combustible gases, including methane. The amount of methane gas present can be determined separately by controlling the temperature of the filament in the gas detector.

Determination of gas in the cuttings is made by placing a small amount of cuttings with a known quantity of water in the closed container of a high-speed grinder. The grinding and agitation liberate the natural gases that are mixed with the air in the container. This air-gas mixture is tested for total gas and methane gas in the manner described above.

All oils, whether crude or refined, fluoresce under ultraviolet light. A sample of drilling mud may be viewed directly under ultraviolet light when it has first been treated to reduce surface tension and gel strength. The relative amounts of observed fluorescence are used as a basis for indicating the magnitude of the oil "shows." Freshly washed cuttings may be examined directly under ultraviolet light for the fluorescent effect of oil.

Since the cuttings are examined in a routine fashion for oil and gas, the same samples may be examined under the microscope and estimates made of the percentage of sandstone, shale, limestone, and anhydrite. A curve showing a percentage estimate of the amount of sandstone in the cuttings is shown in Fig. 4.

A drilling-rate curve is obtained from data provided by depth

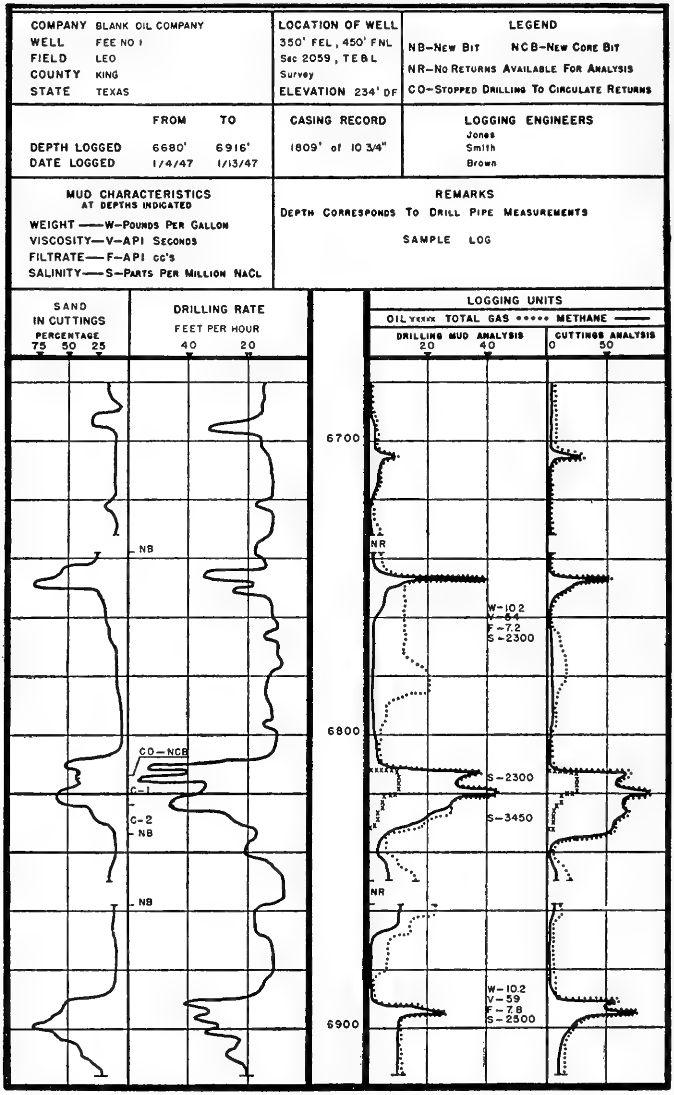

FIG. 4. An example of a drilling-rate log. This log shows continuous instrumental logging of a well bore in which percentage of sand in the cuttings and drilling rate, in feet per hour, are shown on the left side of the log. On the right side of the log, oil, total gas, and methane are indicated from analyses of both the drilling mud and cuttings. (Courtesy of Baroid Well Logging Service.)

meter, pump-stroke counter, and pump-rate meter. The drilling rate is shown in feet per hour. Direct correlations between depth positions of sand cuttings, increased rates of drilling, and depth positions of oil and gas are immediately apparent from such a log. This type of combination log has much value in the drilling of wildcat or exploratory wells. Continuous mud and sample logging affords a direct basis for deciding which formations in a wildcat well should be cored. In the Permian basin of west Texas it is difficult to obtain good electric logs owing to such factors as thick limestone sections and high saline content of the drilling muds. Mud and cutting analysis logging affords a means of supplementing the log data that can be obtained.

CORES

The ideal source of information from a well is a core of the formations penetrated. To core a well is an expensive procedure, and for this reason coring usually is restricted to the producing zones or formations that may be productive of oil or gas. Coring has received considerable impetus in the past few years by the general use of the diamond bit. With it more complete recoveries of the softer formations are obtained, and in hard formations it is sometimes actually cheaper to diamond-core than to drill with the conventional bit. For many years water-base muds have been used, but in the past several years petroleum engineers have been turning more to the use of oil-base muds for coring. Both types of mud partially flush out the original fluids of the core. Oil-base mud, however, is more practical when oil pay sections are being cored above the water zone in reservoir sands. The water content of such cores is bound to be more nearly representative of the original water in place than would be the case if water base mud were used.

As soon as a core is taken from the core barrel, it is washed and described. The examination may be aided by the use of a binocular microscope. It is next taken to the laboratory, where it is tested by the reservoir engineer for porosity, permeability, oil and water content, capillary pressure, etc. Figure 5 is an example of the plotted description of a producing formation with the results of porosity and permeability determinations restricted to that portion of the cored interval capable of producing oil and gas. Some of the properties of a reservoir sand are discussed in the section on permeability in Chapter 32. Cores, rather than sample cuttings, are essential for such detailed studies. The geologist uses core samples principally for studies of texture of clastic grains, microfossils, qualitative and quantitative

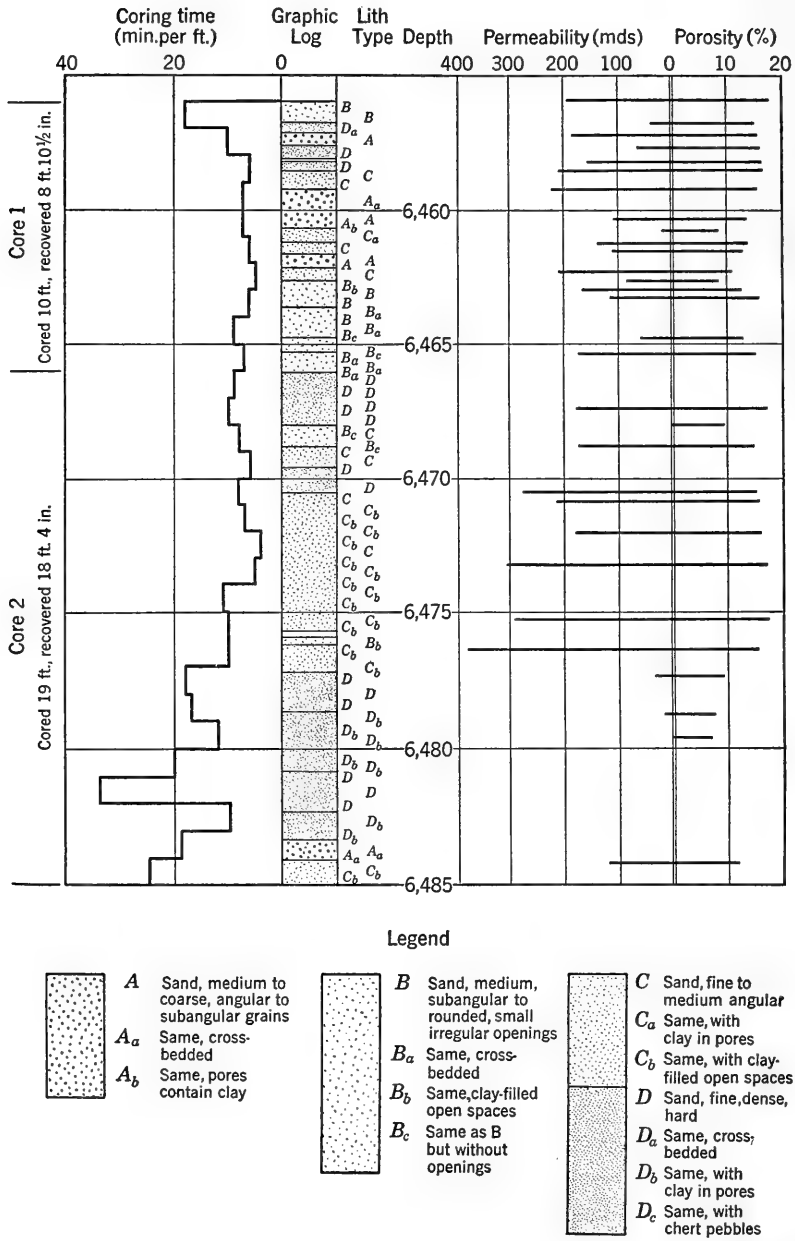

FIG. 5. A graphic log. This log shows cored intervals, drilling time, lithology, depth, permeability, and porosity of a productive sandstone. (Courtesy of The Carter Oil Co.)

study of heavy minerals, relative amount of insoluble residues, and for detailed correlation of individual strata of a producing formation within a reservoir.

TEXTURE

Some textural properties of sandstones and shales are of considerable interest in studies of basin configuration, direction of source, etc. Such properties include grain size, shape and roundness, surface texture, orientation of elongate grains, and degree of cementation. To date, the results of studies of these properties have been of little direct value in the business of finding oil, but the potentialities are great. Numerous techniques have been developed for the preparation of sample materials and their study for such textural parameters. For a short historical development of this subject the reader is referred to Krumbein (1932, pp. 89–124).

MICROPALEONTOLOGY

Microfossils, principally foraminifera, have been used widely in many regions as an aid in stratigraphic correlation. Their minute exoskeletons frequently occur in limestones, muds, and silts. Many forms are widely scattered, both vertically and horizontally in the rock, whereas others are quite restricted in their vertical range, abundant and widespread in their horizontal distribution. The latter forms are true index fossils and are of great value in establishing correlations from well to well. Microfossils may be separated from either cores or cuttings by partially disaggregating the sample and boiling it in water containing a little sodium bicarbonate. Alternating washing and decanting of the sample material under a stream of water will remove most of the non-fossiliferous rock, leaving behind a concentration of foraminifera. Such materials are then ready for binocular examination by a micropaleontologist, who identifies the index forms and notes their stratigraphic position and relative abundance.

HEAVY MINERALS

All sandstones and sandy limestones contain minor and variable amounts of "heavy minerals" which afford another tool in stratigraphic correlation. Heavy-mineral assemblages may vary considerably from formation to formation but remain quite characteristic over a considerable area within a single formation. In making a heavy-mineral study of a formation, the usual procedure consists in determining the relative amounts of the different minerals present. A heavy-mineral separation is effected by immersing a disaggregated rock sample in a heavy liquid such as acetylene tetrabromide or bromoform. Rittenhouse (1948, p. 6) clearly summarizes the technique of heavy mineral-separation:

> Acetylene tetrabromide of specific gravity 2.93 is placed in a glass funnel to the stem of which is attached a piece of rubber tube closed by a pinch clamp. The sand sample is introduced, and the mixture is stirred at intervals until the heavy minerals have settled into the stem of the funnel. The pinch clamp is opened and the heavy fraction is washed onto a filter paper in a second glass funnel. After the excess heavy liquid has been filtered into a receptacle and returned to the stock bottle, the filter paper containing the heavy minerals is washed several times with alcohol. The light minerals and remaining heavy liquid are then drained onto another filter paper, the heavy liquid is filtered off, and the light minerals washed with alcohol. Both heavy and light minerals are dried in an oven at 205° F. The alcohol-tetrabromide washings are saved for recovery of the tetrabromide.

The heavy minerals themselves may be further separated by the use of still heavier liquids than acetylene tetrabromide and bromoform, but it is seldom necessary to make more than the initial separation. Fields of different magnetic and electrostatic intensity are also used to differentiate the heavy-mineral fraction.

The heavy minerals commonly isolated by a heavy-liquid separation are andalusite, apatite, cyanite, epidote, tourmaline, zircon, rutile, chromite, barite, magnetite, pyrite, hematite, garnet, ilmenite, staurolite, topaz, muscovite, and biotite. The percentage of mineral types in a random sampling of 100 or more grains usually suffices to characterize the heavy minerals of one separation. In some samples the variety of heavy minerals is of significance, whereas, in others, the percentage of one or more of the mineral components of the assemblage is more important from the standpoint of correlation. The percentage composition of color varieties may be determined for a given formation. In addition, the percentage of euhedral, subangular, and round grains of several of the heavy-mineral components may be determined. These percentage values for one or more mineral characteristics may be plotted and contoured on a map. Rittenhouse (1948, p. 14) suggests such maps as "roundness maps, tourmaline variety maps, zircon roundness maps, zircon variety maps, and authigenic tourmaline maps." From such maps, usually drawn for individual formations, progressive changes of any physical feature and geographic variations in mineral characteristics may be noted. Such maps are of considerable help in interpreting the source of the sediment, conditions of accumulation, and paleogeographic distribution of the sea in which it was deposited.

USES OF SUBSURFACE DATA

All the methods of obtaining subsurface data, discussed above, were developed in an effort to obtain the most precise information possible on the rock formations penetrated in the drilling of a well. The principal use of such data is to establish the lithologic sequence and then correlate the different formations between wells and between pools. This is followed by the construction of structure maps on key beds above, below, or at the top of a producing formation. Atwill (1942, p. 156) has illustrated a typical example of a structure section which is reproduced in Fig. 6. This profile was drawn with a sea level datum; thus, the three formations illustrated all dip to the east. The Gatchell sand (lowest formation shown) thickens abruptly and rises in the stratigraphic section in a seaward (east) direction from the ancient shore line. This fact, together with the occurrence of very carbonaceous to coaly material in the silt beds below the top of the Green sand updip from the Gatchell, is indicative of an offshore bar origin for the latter formation. It may be noted that the oil-water and gas-oil contacts of this reservoir sand are essentially horizontal and parallel.

SHORE-LINE TRENDS

It is essential to establish the principal shore-line trends at the outset of a subsurface stratigraphic study. This can best be accomplished by trial correlations of several well logs, whether they be of the electric, radioactivity, sample, or drillers' type, or combinations of all four types. The prime consideration is to select what appears to be a genetic sequence of strata devoid of unconformities. Such a sequence usually has a nearly uniform thickness and similar lithology in the direction of shore-line trend. A trial profile laid out normal to this trend usually thickens in a basinward direction. Three or four representative well logs are usually sufficient for the purpose of establishing principal direction of the shore line. Once a probable shore-line direction has been ascertained, it can be readily traced by the use of additional logs selected from wells drilled in the direction of this line. Changes in the trend of a shore line usually can be recognized by a change in thickness of the stratigraphic interval being correlated. An increase in thickness usually means that the trend of the shore line is curved in a landward direction and, conversely, a decrease in thickness of interval means that the shore line is curving in a seaward direction, and a more seaward well log must be selected. Unconformities any-

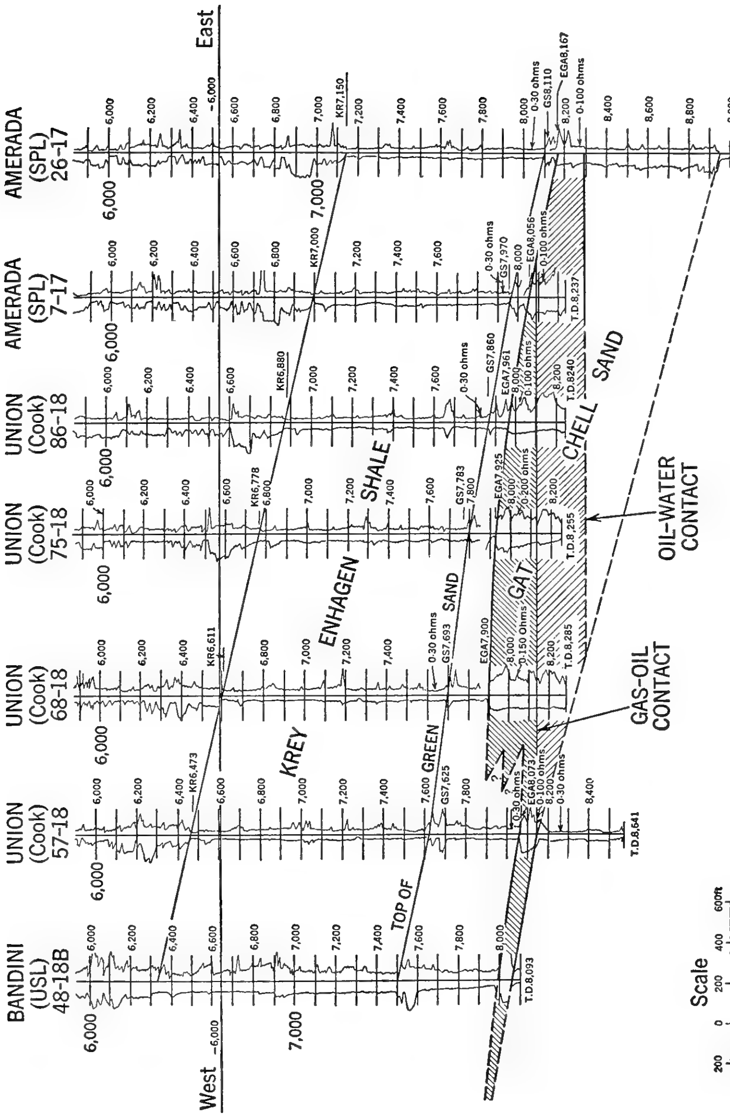

FIG. 6. Structure section at Northeast Coalinga Oil Field, showing bar-like character of producing sand (Gatchell). (After Atwill, 1942, p. 156.)

where within the interval being mapped will result in thinning that is not indicative of the true thickness configuration. Isopach (thickness) maps are usually of much value in determining progressive changes in shore lines.

LATTICE CONTROL OF CORRELATION PROFILES

Once the principal directions of shore-line trend become known in a general way through the method outlined above, the next step is to establish a series of correlation profiles, several of which should be as nearly parallel to the shore line as possible and several normal to it. The spacing and number of profiles depends entirely on the size of the area, number of reliable logs available, and the complexity of the stratigraphy. In many areas six-mile spacing of profiles along townships and ranges should be sufficient. Two such series of profiles will naturally intersect each other at wells common to both and at approximate right angles. The result is a lattice control of the stratigraphy of the entire area. Many details of stratigraphy can be gleaned only from closely spaced wells, especially where sands are lenticular, where unconformities are present, or where the structure is complicated by faulting. These and other significant details can be worked out by "tying in" all well logs which do not happen to lie on a profile into the nearest profile log that occurs in a shore-line direction with respect to the log in question. In many portions of the Mid-Continent an accurate lattice control can be established by using a combination of electric logs and sample logs. Drillers' logs and scout-ticket stratigraphic information then can be correlated readily. In such an area as the Appalachian Basin, where electric logs are almost non-existent, one must rely solely on sample and drillers' logs. This is difficult at best, but has one advantage in that nearly all wells are drilled with cable tools, hence the better sample material. In such an area considerable discrimination must be exercised in the selection of representative logs for the lattice profiles. Visual comparison of numerous closely spaced logs, especially logs of wells in a pool, facilitates the selection of the proper logs. Careless or generalized logging usually can be detected readily.

Sections that have dog-legged trends are probably the least informative profiles to be found in the literature, for under certain conditions they may be parallel, diagonal, and normal to the shore line and pass in and out of the same facies several times. A sand body in one well with no apparent lithologic counterpart in the wells on either side of a profile will be mapped as a lense, whereas often a more judicious selection of wells would prove this sand to be a wedge with its elongate direction parallel to the shore. Unconformities are nearly impossible to recognize from dog-legged profiles owing to the *apparent* lack of systematic change in sedimentary sequence.

LITHOFACIES

When all wells have been "tied" in to a lattice control, it is a comparatively easy task to identify and outline known pools of oil and gas by individual sandstone or limestone formations. A direct comparison of the positions of oil and gas pools with the variations in thickness of the formation in which they occur sometimes makes it possible to relate the incidence of these hydrocarbons to a certain range in thickness. In addition to thickness maps, Krumbein (1945, pp. 1254–1259) has outlined numerous other contour-type sedimentary maps which can be constructed to show attributes of sedimentary rocks, some of which might bear apparent relationship to the occurrence of oil and gas. In a later paper Krumbein (1948, p. 1910) emphasizes the desirability "of contrasting the clastic components and non-clastics in the section" being investigated. He points out that

> A first approximation to the over-all lithological character of a measured outcrop of subsurface section may be had by grouping the rocks into clastics (conglomerate, sandstone, shale) and non-clastics (limestone, dolomite, evaporite) on the usual conventional basis. The thicknesses (or percentages) of clastics are added together and divided by the sum of the thicknesses (or percentages) of the non-clastics. The resulting number is defined as the "clastic ratio." The clastic ratio is augmented by a "sand-shale ratio," which is the ratio of sandstone (plus conglomerate) to shale in the section, regardless of the amount of non-clastics present:
>
> $$\text{Clastic ratio} = \frac{\text{conglomerate} + \text{sandstone} + \text{shale}}{\text{limestone} + \text{dolomite} + \text{evaporite}}$$
>
> $$\text{Sand-shale ratio} = \frac{\text{conglomerate} + \text{sandstone}}{\text{shale}}$$
>
> These ratios may be readily visualized by considering them as indices of the relative amounts of material in the numerator of the ratio deposited per unit thickness of material in the denominator.

Besides isopach, clastic ratio, and sand-shale ratio maps, several additional types of lithofacies maps are of considerable value in a study of sedimentary rocks. They include

1. Ratio of $\dfrac{\text{sandstone} + \text{clastic limestone}}{\text{shale}}$.
2. Ratio of $\dfrac{\text{sandstone}}{\text{shale} + \text{limestone}}$.
3. Number of quartz-sandstone beds.
4. Average thickness of quartz-sandstone beds.
5. Composite thickness of quartz-sandstone beds.
6. Average thickness of all beds.

For the petroleum geologist the object of constructing all such maps is to ascertain any apparent relationships between the trends and numerical values of isolithic lines and the incidence of oil and gas. Undoubtedly numerous additional types of maps can be drawn for the purpose of showing various properties of sediments, but all the types indicated above can be constructed from data available from any of the several types of well log and core information usually available to the student of subsurface geology.

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CHAPTER 32

POROSITY, PERMEABILITY, AND CAPILLARY PROPERTIES OF PETROLEUM RESERVOIRS

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The production of oil involves the flow of oil, gas, and water through porous rocks. To obtain the most complete and efficient recovery the flow must be controlled. Intelligent operations thus require an understanding of the behavior of fluids in porous media. The search for new pools requires a better understanding of the mechanisms that control the migration and accumulation of oil. The capillary behavior of the three separate fluids, oil, gas, and water, in the porous medium depends partly on the physical and chemical properties of the medium. Some of the important properties of the medium are porosity, permeability, and pore pattern, all of which are controlled by the petrographic texture of the rock.

Porosity, permeability, and capillary properties are measurable, and they serve to characterize the porous medium. Porosity controls the amount of space available for fluids. Capillary properties control the amount of interstitial water and therefore the amount of pore space available for oil. Permeability controls the rate at which the fluids will move under a given pressure differential. The effective permeability to any one fluid, however, depends on the amount of pore volume occupied by that fluid. As flow continues, the relative amounts of the different fluids change, and therefore their effective permeabilities change also. The ratio of the permeability of the rock to oil to its permeability to gas or water determines the efficiency of the recovery mechanism, and this ratio continually changes. The determination and prediction of these permeabilities and their ratios not only require a more complete knowledge of the physical properties of the substances than we now have, but also involve difficult unsteady-state flow problems. Satisfactory formulas describing and predicting the production of oil, gas, and water have never been solved, although they are needed to govern decisions regarding the spacing of wells and optimum production rates, which are of very great economic importance. It is obvious, for example, that often in the past well spacings have been closer than can be economically justified, and production rates have sometimes been too fast for efficient recovery. Laboratory investigations of the permeability and capillary properties of oil and gas reservoirs are needed to guide petroleum-production operations and are therefore proceeding actively in many industrial and academic laboratories.

PETROLEUM RESERVOIRS

Oil pools are found in geological formations of widely different age, character, and structural configuration. All commercial pools, however, are found in a porous reservoir rock, enclosed, at least over its upper surface, by a caprock such as shale or dense limestone that is impermeable to oil or gas. Some oil reservoirs are filled almost entirely with oil. In others the uppermost portion of the reservoir is filled with gas, and even when gas caps are absent there is nearly always some gas dissolved in the oil. Some reservoirs contain only gas consisting of methane with varying amounts of heavier hydrocarbons that can be condensed to form gasoline. When these are abundant, the reservoir is called a condensate pool. Many condensate pools have a narrow rim of liquid oil down-dip around their margins.

Water in Oil Reservoirs

The porous reservoir rock nearly always contains at least some water, segregated from the oil at a lower level. In some reservoirs this water-saturated rock extends long distances below and beyond the limits of the oil pool, whereas in others the porous zone is restricted laterally and filled almost completely with oil. The water is believed to be the buried remains of the sea in which the sediments were deposited, but it is generally more concentrated than sea water. The concentration in a given horizon usually increases with depth of burial. Oil-field brines vary widely in composition but generally contain more calcium, less magnesium, and much less sulphate than sea water in proportion to their sodium and chlorine content.

Until recently it was believed that the oil-bearing portion of the reservoir contained only oil, because wells completed above the water-oil contact produced no water. Fettke (1927), who was one of the first to determine the oil content of sand, reported the presence of water also, which was generally believed to have entered the sand during the drilling of the well. It was later proved (Schilthuis, 1938) that water is present in oil and gas sands. Indeed, on the basis of both theory and experiment, water should be present, for during its accumulation the oil must have had to displace water from the pores, and a certain fraction of this water is necessarily retained by capillary forces or otherwise trapped. Later work has shown that the water saturation is always appreciable and sometimes amounts to half or more of the pore volume. The acceptance of the presence of water in the sand caused a profound change in geological thinking. It had previously been thought that the oil occupied all the pore volume of the sand, of which only a small fraction was being recovered. If between $\frac{1}{10}$ and $\frac{1}{2}$ of the pore volume is occupied by water, the recovery efficiency is somewhat greater.

Production by Solution Gas Drive

When the formation is first penetrated by the drill, the fluids are found to be under normal hydrostatic pressure, that is, a pressure approximately equal to that of a column of salt water extending to the surface. The withdrawal of oil or gas causes immediately a zone of lower pressure among the fluids in the vicinity of the well bore. If the sand near the well contains mostly oil, its effective permeability to oil is high, and the effective permeability to water very low. Consequently the flowing stream consists entirely of oil, containing gas in solution. As the oil rises in the well toward the surface, its pressure decreases, and the gas comes out of solution. The gas bubbles expand and lighten the column, so that a froth of oil and gas is expelled at the surface, sometimes with great violence.

The low-pressure zone around the well bore rapidly expands, and, after a certain amount of oil has been withdrawn, the pressure in the fluids for a considerable distance radially from the well is less than the saturation pressure of the gas. When this occurs, the gas comes out of solution in the pores of the sand. At first the small bubbles move the oil, but later they coalesce and move as a separate flowing phase toward the well. This process has a very deleterious effect on the productivity of the well. The effective permeability of the sand to gas increases rapidly while that to oil decreases, and consequently the gas production of the well increases and the oil production decreases. The production of fluids has been largely brought about by the pressure gradient maintained by the expansion of the gas originally dissolved in the oil. When this gas is able to travel freely to the well bore, driving only small quantities of oil before it, the efficiency of the recovery mechanism falls off very rapidly. Furthermore, the amount of gas is limited, so that eventually its flow decreases also. The loss of gas from solution causes a volume shrinkage of the oil which is nearly always appreciable and may be large. This decreases the oil saturation and reduces the effective permeability of the sand to oil still further. It also increases the viscosity of the oil and consequently decreases its flow.

The great majority of oil pools have been produced by this depletion mechanism (Mullane, 1944), which is known as "dissolved-gas drive."

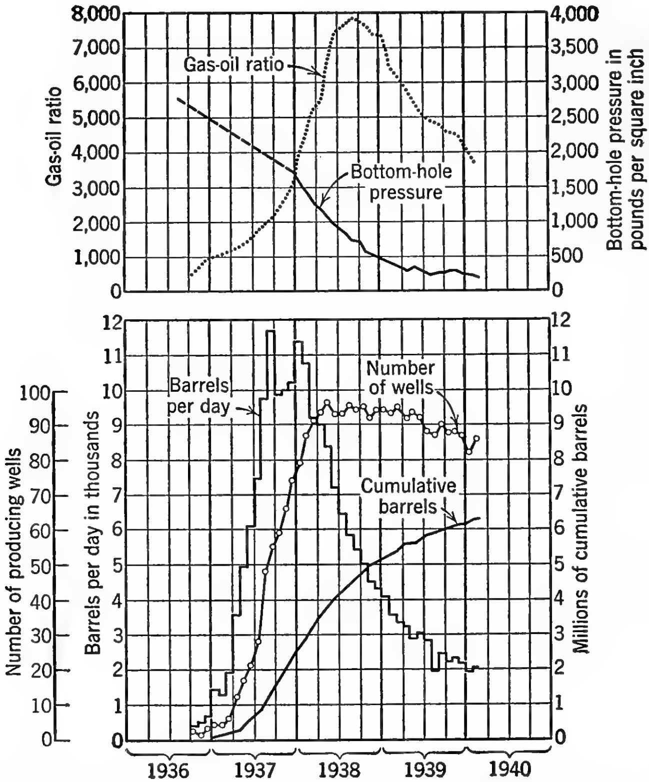

FIG. 1. Graphical statistics of Northwest Gloyd Extension of the Rodessa Field. (After Mullane, 1944, p. 54.)

The graph of production against time follows a very definite pattern. The oil flow reaches its maximum during the first few weeks, and after a few months it is declining rapidly. The decline continues, but the rate of decline diminishes, and, if the logarithm of the production is plotted against the logarithm of time, the production-decline curve is approximately a straight line. Meanwhile the gas-oil ratio, usually expressed as cubic feet per barrel, increases rapidly from that originally dissolved in the oil to a high maximum and then falls as the gas supply is exhausted. Figure 1 shows the oil production and gas-oil ratio history of the Northwest Gloyd Extension of the Rodessa Field (Louisiana), illustrating behavior typical of the solution-gas drive.

The rapid increase of the effective permeability of the sand to gas and the limited amount of gas available make the recovery efficiency of the dissolved gas drive mechanism very low. When the total liquid saturation has dropped to about 70 percent, of which 50 percent may be oil and 20 percent water, the flow of oil has practically ceased, and the well may produce only a few barrels per day. Thus only from 20 to 30 percent of the oil originally in place will have been produced at the exhaustion of the field.

Oil Production by Water Drive

In pools where a large aquifer exists below or marginal to the oil zone, the water tends to move into the pool and displace the oil. Water is a more efficient driving agent than gas, partly because it has a more favorable relative permeability relationship to oil, and partly because it has a much higher viscosity. If, therefore, a steady and uniform advance of the edge water or bottom water can be maintained, a much more efficient recovery can be realized; under favorable circumstances as much as 85 percent of the original oil in place. In the past, however, full use has not been made of this mechanism. Usually the drive of the water is caused mainly by its volumetric expansion resulting from the drop in pressure. Unless there are very large amounts of water in the aquifer, so that the additional volume provided by this expansion is roughly equal to the volume of fluids withdrawn, the advance does not continue. Owners of "edge" leases were forced to pump the water out along with the oil or lose their entire production, and this withdrawal is frequently enough to stop completely the encroachment of the water. Recently, with a better understanding of the value of the water drive, it has been possible to take advantage of it in various ways. If production is restricted, as by a state regulating authority, withdrawals from a pool can be held to a point where the advancing water is able to maintain the pressure in the oil reservoir. Figure 2 shows the production history of the North Searight Pool (Oklahoma), where the bottom-hole pressure remained high and an efficient recovery was obtained. If the natural advance of the water into the reservoir is too slow, special water-injection wells may be drilled in the water zone and pressure maintained by pumping additional water into the sand. Water wells may be drilled on a definite pattern between the oil wells, and numerous sources of water may be provided. The latter method has been extensively applied as a secondary recovery

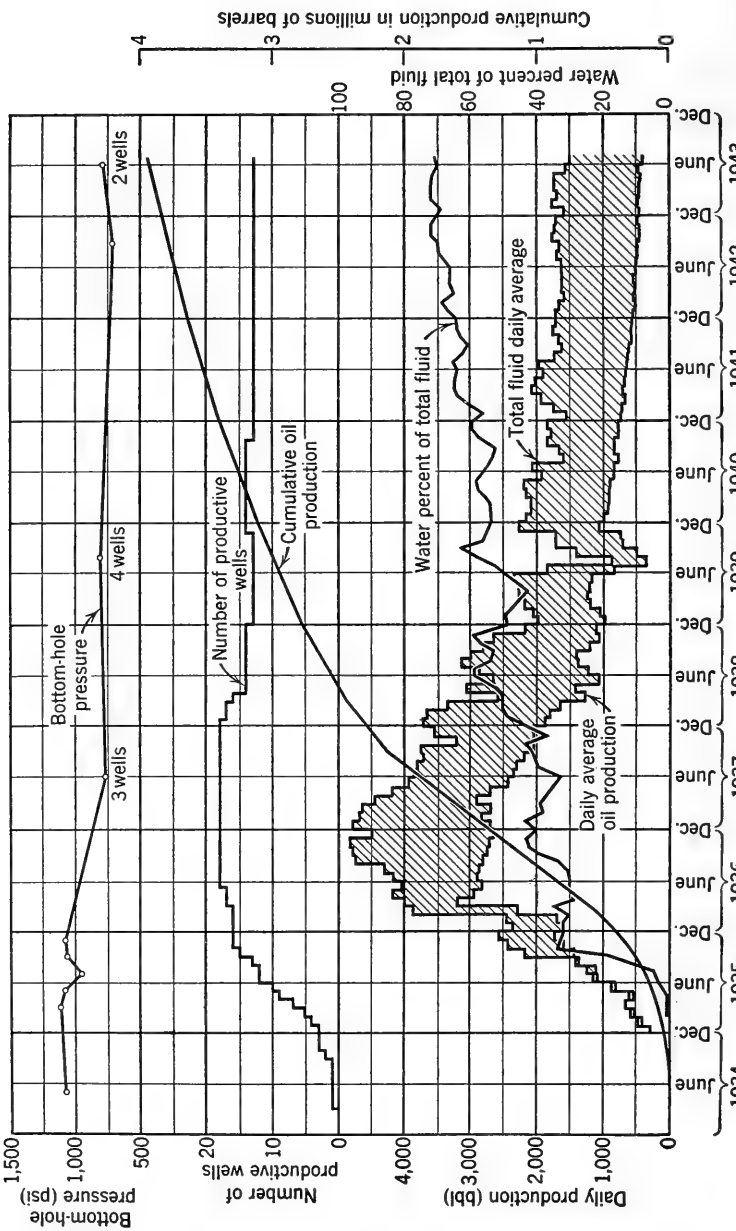

FIG. 2. Production statistics of North Searight Pool. (After Mullane, 1944, p. 61.)

development in many pools that had been virtually exhausted by the solution-gas mechanism; it is generally called "water flooding."

Production by Gravity Drainage

In certain reservoirs of relatively high permeability and steep dip, oil is able to flow down the dip by gravity alone. Good recoveries can be obtained when this occurs because the oil is not retained to such a large extent by capillary forces and can be recovered from the down-dip wells. The rate of recovery, when gravity drainage is effective, can be increased by reinjecting the produced gas at the top of the structure. This maintains the pressure in the reservoir and results in a more rapid movement of the oil down the dip. The recovery from the Oklahoma City pool would have been much less if the high permeability of the sand had not permitted the oil to run down-dip and accumulate in the lower parts of the reservoir.

POROSITY AND PERMEABILITY OF OIL RESERVOIRS

Early Studies

The first large-scale production of oil and gas occurred in northwestern Pennsylvania in 1860. Early speculations regarding the nature of underground reservoirs dealt mainly with crevices or caverns. Some years later Carll, of the Pennsylvania Geological Survey, worked out most of the important features of petroleum reservoirs and their behavior. Carll (1880) showed that the producing sandstone had a porosity between $\frac{1}{10}$ and $\frac{1}{15}$ of its bulk and that it was capable of holding up to 1,000 barrels of oil per acre-foot of rock. He also showed that the aggregate area of the pores was ample to transmit large quantities of oil. He also pointed out that the removal of oil from a reservoir required the admission of some other fluid to take its place, suggesting the deliberate injection of water for this purpose.

Darcy (1856) studied the behavior of sand filters and discovered the law that now bears his name. As later formulated, it states that the flow of water Q through the porous medium per unit cross section is directly proportional to the pressure gradient $\partial p/\partial x$ in the fluid. The constant of proportionality is k/μ, where μ is the viscosity of the fluid and k is a constant depending on the matrix through which the fluid flows.

$$Q = \frac{k}{\mu}\frac{\partial p}{\partial x}$$

King (1898) published extensive experiments on the transmission of water and air by porous media. At the same time Slichter (1898) made a theoretical study of porosity and permeability. He showed that spheres of equal size could be packed in various configurations, and that the volume of the interstices would range between 26 and 47 percent of the bulk volume, depending on the packing. He attempted to apply the laws of Poiseuille governing the flow of fluids through pipes to the pores between the spheres, and he found that the permeability should be a function of the porosity and the square of the grain diameter. He also derived a formula for the radial flow of water into a well. His attempts to apply the laws of fluid flow in pipes to porous media were greatly oversimplified, for they did not take into account the wide variation in pore size in natural reservoirs or the mutual interconnections of the pores.

In spite of the direct applicability of this work to the problems of oil production, very little use of it was made by the oil industry. In fact, porosity and permeability were generally confused by petroleum engineers and geologists for many years, even though Slichter distinguished them clearly and showed that they were partly independent of each other. About 1920 the introduction of gas and water into the depleted oil pools of Pennsylvania began, and research on the behavior of fluids in underground reservoirs was sponsored by the oil producers of that area. Interest spread quickly in other regions, and fundamental studies have continued, in an expanding manner, to the present time.

Porosity

The porosity of a porous medium has been defined in soil mechanics and in the petroleum industry as: "The property possessed by a rock of containing interstices, without regard to size, shape, interconnection or arrangement of openings. It is expressed as the percentage of total (bulk) volume occupied by the interstices" (A.P.I., 1941; Tolman, 1937). It is also possible to classify porosity as to type. For example, *effective porosity* is that property possessed by a rock of containing intercommunicating interstices. Similarly, *isolated* porosity is that property of a porous medium of containing non-communicating interstices. In making such a fine distinction in porosity, it is at once apparent that the quantitative determination of these values is a function of the laboratory method used.

One of the most common methods used for determining porosity is to take a sample of rock, extract the fluids and soluble materials present, and obtain the bulk volume of the sample either by direct measurement or by observing the volume of liquid displaced when the sample is totally submerged in the liquid. A dry weight of the sample is taken, and the interstices of the rock are filled with a liquid of known density. The weight of the rock plus the liquid is thus obtained. The pore volume can then be calculated by subtracting the dry weight of the rock from the weight of the rock plus liquid and dividing this difference in weight by the density of the liquid. The pore volume divided by the bulk volume is the fractional porosity, which when multiplied by 100 expresses the porosity in percent. When such a determination is examined critically, a number of specific points can be noted. For example, if there were extractable solids in the rock which were not part of the fluid phases in the interstices but actually a part of the matrix of the porous medium, the determined value for the porosity would be higher than the actual porosity. In some instances, it is possible for the rock to contain swelling clay particles in the interstices. In an aqueous phase, this swelling is a function of the ionic strength of the dissolved salts. The swelling is greater in fresh distilled water than in brine. Hence it is possible that a different pore volume would be obtained for each type of fluid used for saturating the interstices, although this effect is small. If the sample of rock is so small that experimental errors arise in the determination of bulk volume, such inaccuracies would be carried over in the calculation of the final porosity values.

There are several other methods of determining porosity. One method is to take a sample of clean, extracted, dry rock, measure its bulk volume, and obtain a dry weight. This dry weight divided by the rock grain density, which for silica is about 2.65 grams per cubic centimeter, gives the grain volume. The pore volume is the grain volume subtracted from the bulk volume. The percent porosity would then be

$$\frac{V_B - V_G}{V_B} \times 100 \tag{1}$$

where V_B is the bulk volume and V_G the grain volume. This method is fairly accurate for clean sandstones and limestones.

A method often used in the oil industry for routine core analysis is the Washburn-Bunting technique, which makes use of a mercury-evacuation method to remove the air from the voids in the porous medium. The volume of air corrected to the proper conditions is then measured, and this is the pore volume. The porosity is computed as shown above. Another technique is to force mercury into a clean core under pressure. The volume of mercury forced into the porous medium under these conditions is close to the pore volume. The porosity is then computed as shown above. Some investigators have attempted to estimate porosity microscopically by obtaining a statistical average of the void space on a thin section. As will be shown later, porosity is related to grain size, interstitial surface area, and permeability. In fact, for clean unconsolidated sands, a fair estimate of porosity can be made if the permeability is known and if the interstitial surface area is measured by the gas-adsorption method (Brunauer, 1943; Carman, 1941). It is impossible in such a short discussion to treat all the methods used for determining porosity. However, it is felt that the examples given above will introduce the reader to the complexity of the subject and point out to him some of the advantages and disadvantages of the more common techniques.

PERMEABILITY

Fancher, Lewis, and Barnes (1933) made an extensive investigation of the permeability of various consolidated and unconsolidated materials. Wyckoff, Botset, Muskat, and Reed (1934) showed that the effect of the viscosity of the fluid should be separated from formulas expressing fluid flow, and that a constant could be used to express the transmissibility of the porous medium. Although, as Slichter deduced, the permeability constant should depend on the square of the pore diameters, the complexity of the pore system in natural porous media is such that none of these investigators was able to derive a valid relation between the geometrical constants of the medium and its permeability.

Darcy's law was introduced above together with a constant of proportionality k, which was characteristic of the matrix through which oil, gas, and water flow. It is now possible to identify this k with permeability, recognized by the American Petroleum Institute: "A measure of the fluid-transmitting capacity of a porous medium. The unit of permeability is the darcy. A material has the permeability of one darcy when one atmosphere pressure differential across one centimeter length causes a viscous flow of one cubic centimeter per second of a fluid of one centipoise viscosity through a cross section of one square centimeter" (A.P.I., 1941). In conformity with A.P.I. Code 27 (1942), numerous permeameters of different design exist for measuring permeability. Fundamentally, a permeameter consists of a suitable core holder, a pump for forcing fluid through the core, a manometer to measure the pressure drop across the core, and a flow meter for measuring the rate of flow of fluid through the core.

Leas has devised apparatus for measuring the permeability of porous material to air with an accuracy sufficient for use in most petroleum-reservoir engineering applications (in preparation). This permeameter is shown schematically in Fig. 3. M_1 is a manometer for measuring the pressure drop in the air phase across the core; M_2 is a manometer for measuring the absolute pressure within the system. The elements of the pump for forcing air through the core are contained within the dotted area of the diagram. Two bulbs are filled partially with water

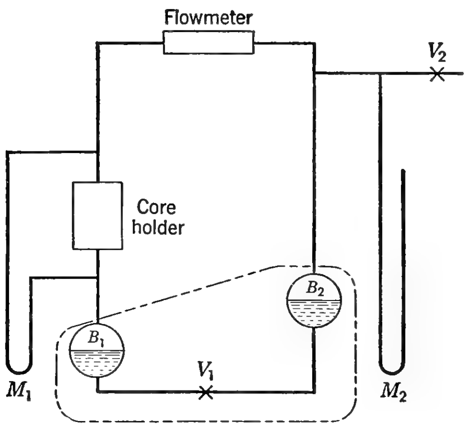

FIG. 3. The Carter gas permeameter.

the rate of flow of which from B_2 to B_1 is controlled by valve V_1. When V_1 is opened slightly, water flows from B_2 to B_1 at a steady rate. The water entering B_1 decreases the air volume therein, and the air pressure increases. Simultaneously the air pressure in B_2 decreases because of the water flowing out. The net result is a pressure difference across the core measured by the manometer M_1. The flow is measured by the displacement of a soap film up the bore of a vertical calibrated glass tube.

The permeability is calculated from Darcy's law:

$$k = \frac{\mu q L}{\Delta P A}$$

where k is the permeability in darcys, q the volume rate of flow in cubic centimeters per second, μ the viscosity of gas in centipoises, L the length of the core in centimeters, A the cross-sectional area of the core in square centimeters, and ΔP the pressure difference across the core in atmospheres.

Klinkenberg (1941) observed that the permeability of a core to gas is greater than the permeability of the same core to a liquid, and that the gas permeability is a linear function of the reciprocal of the absolute pressure of the gas flowing through the core. When this curve is extrapolated to infinite gas pressure, the gas permeability is the same as the liquid permeability. With the above apparatus it is possible to measure this Klinkenberg effect and make the necessary correction to the gas permeability to compute the liquid permeability.

Calhoun and Yuster (1946) made further studies of this phenomenon. They conclude that gaseous permeability is dependent on the mean pressure during flow but is independent of the pressure differential. Although the permeability for different gases was found to be different, all values have been extrapolated to one common permeability at an infinite mean pressure. This permeability was found to be essentially the same as that for liquid flow. No variation of permeability with temperature and surface tension was noted.

Calhoun and Yuster also observed an anomaly of liquid flow occurring when ordinary salt solutions were employed or when standard buffer solutions were employed. With the ordinary salt solutions, an increase of permeability was noted up to a concentration of 1 *N* NaCl. With the buffer, an increase of permeability was observed on each side of the neutral point (*p*H 7). This ionic effect was also supported by the results of Grunberg and Nissan (1943), but it is still not very well understood. It is, however, believed to be associated with some sort of electrokinetic phenomenon.

In such limited space, it is not possible to treat porosity and permeability very completely. A more comprehensive treatment, together with an analysis of Darcy's law, is given by Muskat (1937) and reviewed by Hubbert (1940). From the microscopic viewpoint, one of the best studies is by Carman (1937).

Relative Permeability

The above discussion of permeability applies when only one fluid occupies the interstices of the porous medium. When two or more fluids are present in the porous medium, the effective permeability of the core to one fluid is a function of the saturation of the fluids in the pores. Relative permeability may be defined as follows: If fluids *A* and *B* occupy the pores in a rock, the effective permeability of the rock to fluid *A*, divided by the total or absolute permeability of the rock when only one fluid fills the pore spaces, is the relative permeability of the rock to fluid *A* at this particular saturation of *A*. The relative permeability of the rock to fluid B may be defined in a similar manner.

Botset (1940) measured the relative permeabilities of both unconsolidated and consolidated sand to gas and to liquid. His experimental curves are shown in Fig. 4. The solid lines refer to the consolidated Nichols Buff sandstone, and the dotted lines refer to unconsolidated sand (permeability 17.8 darcys). For both of these porous media the saturation of gas at which gas first starts to flow is at 10 percent.

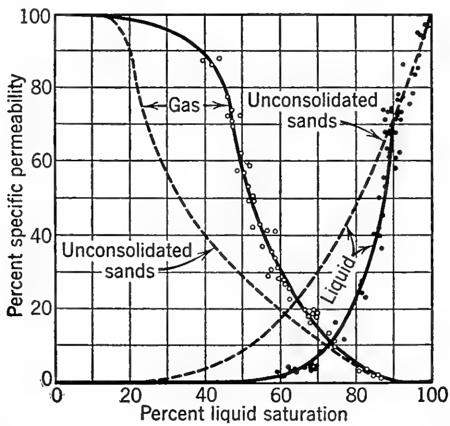

FIG. 4. Permeability-saturation curves. (After Botset, 1940, p. 94.)

This is defined as the equilibrium gas saturation. From 90 to 100 percent liquid saturation, the gas phase is probably present as bubbles which are certainly not continuous. Flow of gas does not occur until the gas phase assumes a continuity. When this occurs and a pressure gradient develops in the gas phase, flow occurs. In this experiment, it is very probable that the liquid or the wetting phase occupies first and then flows through the smallest pores, whereas the gas tends to seek first the larger pores.

When three phases, gas, oil, and water, occupy the pores in a rock, the situation with regard to relative permeability is still more complicated. This was experimentally treated by Leverett and Lewis (1941) for unconsolidated sand. These investigators conclude that, for this system, the relative permeability to water is determined by the water saturation alone and is not affected by the introduction of an additional non-aqueous phase. The relative permeability to gas in three-phase flow is slightly less than would correspond to the same gas saturation in two-phase flow. The relative permeability to oil varies in a more complex manner, being in some regions less and in others more than for the same oil saturations in two-phase flow. The isoperms for all components are independent of the viscosity of the oil phase. Points determined by kerosene and points that use a more viscous blended oil fall along the same isoperms. And, finally, these authors conclude that the presence of appreciable amounts of all three phases in a flowing stream in equilibrium with the fluid in the pore space is limited to a relatively small region of pore composition.

More recently, Morse, Terwilliger, and Yuster (1947) made experimental measurements of relative permeability in two fluid-phase systems. In this method a section of core is placed at each end of and in capillary contact with the sample to be measured. Mixing of the two fluids occurs in the first section, and the end effect of the wetting phase piling up presumably occurs in the third section. It is probable that simultaneous parallel flow of the two fluids takes place in the center section (or sample). This experimental technique appears to be convenient for some routine work. However, with this procedure it is not possible to measure the pressure gradient separately in each of the flowing phases, or to maintain a pressure difference between phases (capillary pressure). It is also necessary to operate this equipment at flow rates which are very large compared to those encountered in an actual petroleum reservoir. At these rates, it is probable that some sort of slug flow may be encountered, that is, alternate slugs of each of the fluids. Rose (1948) and Rose and Bruce (1949) indicate a possible method for computing relative permeabilities theoretically from data taken from measurements of the capillary properties of porous media.

CAPILLARY PROPERTIES

The capillary properties (Rose and Bruce, 1949) of a porous medium are determined by: (*a*) the geometrical configuration of the interstitial spaces in the matrix, as discussed later in this chapter; (*b*) the physical and chemical nature of the interstitial surfaces; (*c*) the physical and chemical properties of the fluid phases in contact with the interstitial surfaces. The measurable macroscopic properties of a fine-grained porous medium are porosity, permeability, and the capillary pressure-saturation behavior of immiscible fluids in the medium. These macroscopic properties depend on the microscopic properties classified above.

It has been recognized for some time that when two fluids occupy the pore space in a porous medium the interfacial boundary between the two fluids is curved (Leverett, 1941; Bruce and Welge, 1947). The degree of this curvature is dependent on the size of the rock pores and the proportions of the fluids present. There is a difference in pressure between the fluids across this interface; it is usually termed the capillary pressure at a particular saturation of the wetting phase. The pressure is sustained by the tension in the surfaces and therefore depends on both the interfacial tension and the curvature. It can be expressed mathematically as

$$P_c = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

where P_c is the capillary pressure, γ the interfacial tension, and R_1 and R_2 the principal radii of curvature of the surface. When R_1 and R_2 are very nearly equal, the equation for capillary pressure can be written

$$P_c = \frac{2\gamma}{R_3}$$

where R_3 is the average of R_1 and R_2. It should be noted that these equations do not assume the porous medium to be a bundle of capillary tubes. For a capillary tube,

$$P_c = \frac{2\gamma \cos \theta}{R_4}$$

where R_4 is the radius of the tube and θ is the contact angle in the wetting phase. In this case the average radius of curvature would be

$$\frac{R_4}{\cos \theta}$$

Capillary pressure is a function of saturation of the fluid phases occupying the interstices of a porous medium. To demonstrate this fact, an experiment may be performed: A porous sample of rock is first completely saturated with brine (the wetting phase) and placed in a cell in contact with a porcelain or cellophane barrier which is permeable to brine but not to gas or oil (non-wetting phases). Such a cell is shown in Fig. 5. The space surrounding the core is then filled with oil or gas. When pressure is applied to the oil or gas, it is forced into the porous sample, and brine is forced out through the semi-permeable barrier. The difference in pressure across this barrier, which is the same as that across the interface between the two fluid phases in the sample, is the capillary pressure. When plotted against the saturation of the wetting phase, it normally provides a curve similar to that shown in Fig. 6.

In this type of experiment, it can be observed that considerable pressure is built up before the non-wetting phase enters the core to displace the wetting phase. Thus for each type of porous medium there is a threshold pressure. This is observed in Fig. 6 as the vertical line at 100 percent saturation of the wetting phase. However, another

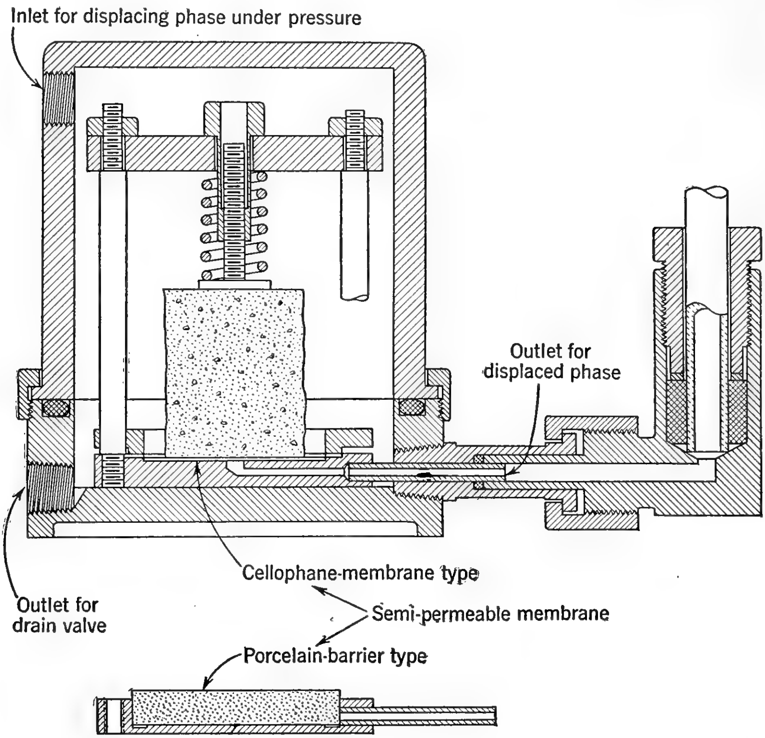

FIG. 5. Single-core displacement cell. (After Rose and Bruce, 1949, p. 129.)

vertical portion of the curve is reached at much lower saturations of the wetting phase. For the Weber sand this saturation is about 30 percent. At this point only small and decreasing amounts of brine are forced out by large increases in pressure. This is called the region of minimum residual brine saturation. The wetting phase has become discontinuous and exists in the form of pendular rings around the grains making up the porous medium. A more complete discussion of this irreducible minimum is given by Rose and Bruce (1949), Leverett (1941), Bruce and Welge (1947), and earlier workers.

The capillary pressure experiment, as described above, has its counterpart in nature. When the sediments were first laid down in geological time, they were sands, rather loosely consolidated, but filled with salt water. This salt water was trapped in the interstices of the sand and existed in this state while other strata were forming on top of the sand, causing consolidation of the porous medium. At some time during geological history, oil migrated under pressure into this brine-filled formation, displacing the brine in the same manner as the wetting phase was displaced by the non-wetting phase in the above experiment. The pressure difference between the oil and the water, which enables the oil to displace water from the pores of the rock, is brought about by their different densities. In a dipping stratum whose pores are jointly occupied by oil and water, the difference in pressure between the two phases depends on the vertical height of the oil column. The pressure difference Δp is given by the equation

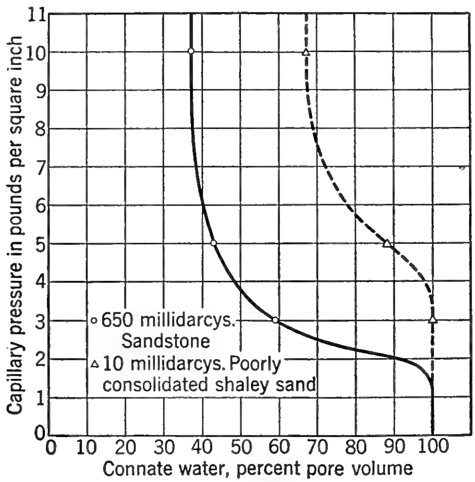

Fig. 6. Restored-state curves.

$$\Delta p = hg(\rho_w - \rho_0)$$

where h is the height above a free water surface of the portion of the reservoir sand under examination, g the acceleration of gravity, and ρ_w and ρ_0 are the densities of the brine and oil phases, respectively. Equilibrium exists when this Δp equals the P_c for the formation. The capillary pressure will be lowest, and the water saturation highest, near the base of the oil column, the "water level." It will be the highest, and the water saturation least, at the highest part of the reservoir.

Bruce and Welge (1947) considered whether a minimum residual water saturation really exists.

Theoretical study of the problem indicates that at some capillary pressure difference the residual water saturation should approach zero provided complete equilibrium is attained. Experimental work on soils at several thousand atmospheres of capillary pressure has shown that near zero water saturation can be produced when the displacing phase is a gas. In practice, laboratory experiments have indicated that, within the accuracy of saturation measurements, a minimum saturation does exist within the range of pressures encountered in reservoirs having less than 1,000 feet of closure.

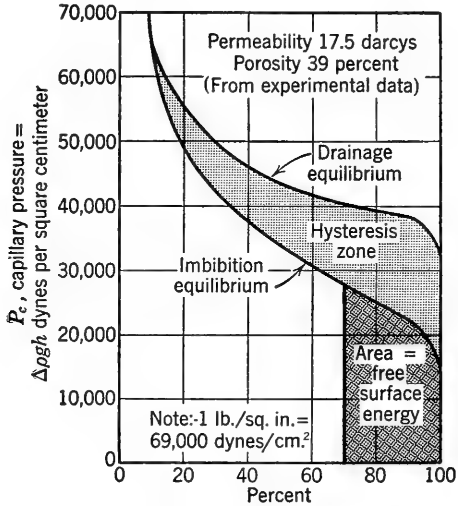

FIG. 7. Equilibrium distribution of air and water in uniform unconsolidated sand, having a permeability of 17.5 darcys. (After Leverett, 1941, p. 163.)

In the discussion above, thus far only the drainage type of capillary pressure *vs.* saturation curve has been discussed. Actually the capillary pressure-saturation curve is different if the data are obtained by imbibition. Leverett (1941) studied this hysteresis zone for unconsolidated sand. Figure 7 gives the results of this study. It is quite possible that the conditions under which hydrocarbons accumulate in and are produced from the earth correspond to the imbibition equilibrium. In this regard, Muskat (1948) points out

. . . that the application of capillary pressure curves obtained by the drainage or desaturation processes to the calculation of the fluid distribution in interphase transition zones involves a number of difficulties, namely: (1) the development of very low non-wetting phase saturations appears to be in contradiction to the lack of mobility of such distributions indicated by permeability-saturation curves, (2) dispersed non-wetting phases are thermodynamically unstable, (3) discontinuous phases should not be subject to hydrostatic requirements.

Muskat states that an assumption that the capillary pressure curve has an initial horizontal segment might eliminate these objections, but it seems more likely that the imbibition curve should be applied to the lower part of the water-oil transition zone. It appears that this is a very controversial subject, which is by no means settled at this time. In fact, tied in with the above is the concept of wettability which appears to govern the mechanism of displacement. Depending on how the fluids wet the rock, the displacement process may follow different mechanisms. If a wetting fluid is displaced by a non-wetting fluid, the wetting fluid is progressively removed so as to occupy always the smallest pores in the medium. Finally, the wetting fluid becomes discontinuous and is separated into pendular rings around the rock grains at this irreducible minimum saturation. The larger pores are thus left free for the passage of the non-wetting fluid through the porous medium. On the other hand, if a non-wetting fluid is displaced by a wetting fluid, the wetting-displacing phase invades preferentially the smaller pore openings and causes a partial trapping of the non-wetting fluid to be displaced. This trapping occurs progressively, isolating portions of the non-wetting fluid that remain in the larger pore openings, until the non-wetting phase becomes discontinuous but not in pendular rings as above. In fact, the smaller pores only are thus left free for the passage of more wetting fluid through the porous medium. It is possible that the actual mechanism of displacement might be a complex combination of the above two mechanisms, as in a sand that is partially water-wet and partially oil-wet.

Hassler, Brunner, and Deahl (1943) give this subject of wettability some thought. These authors present data to show that some wettability information can be obtained by determining capillary pressure-saturation curves on the same porous medium with different combinations of fluids. This again is further complicated by possible trapping of the displaced phase, which gives a false picture of capillary equilibrium.

A clear view of the situation requires a sharp distinction between *viscous* pressure differences, which always occur as gradients proportional to the rate of flow of a particular fluid and which do rise to high values in an oil field, and the *capillary pressure* differences, which always occur as sharp discontinuities in pressure across phase boundaries; which are not associated with viscous flow, and which never exceed the pressure caused by the most highly curved phase boundary in the rock. The capillary pressure is everywhere the same in a rock in equilibrium, although trapped bubbles, which do not have any effect on pressure distribution other than to act as plugs to viscous flow of liquids, may have many curvatures (for a few days). Threshold pressure, being a pressure difference between two points in the same non-wetting phase, involves the difference in curvature between two phase boundaries (opposed meniscuses) and only two wherever, as with real materials, a droplet or bubble of one fluid cannot stop by complete plugging the tendency of a second fluid to relieve pressure differences caused by the plug [Hassler, 1943].

Welge (1948) took cores from a petroleum reservoir, restored them to their natural state by the above drainage-displacement technique, and then attempted to produce the oil from these cores by displacing the oil by brine from below or gas from above. The semi-permeable-barrier technique is again used in the displacement of the oil from the restored cores, but in this instance the porcelain plate is made oil-wet by treating it with silicones.

THE CAPILLARY RETENTION FUNCTION

Leverett (1941) found that when the dimensionless function

$$\frac{\Delta\,\rho g h}{\gamma}\sqrt{\frac{K}{f}}$$

is plotted *vs.* the saturation S_w of the wetting phase in four clean sands, the data fall satisfactorily near two curves, one for the imbibition of water and the other for drainage. K is the permeability of the sand to a homogeneous fluid, f the porosity, γ the interfacial tension, g the gravitational constant, h the height above a free-water surface, $\Delta\,\rho$ the difference in density between the two fluid phases. Rose and Bruce (1949) treat the subject in greater detail and develop the capillary pressure or j function, which is

$$j(S_w) = \frac{P_c}{\gamma \cos\theta}\sqrt{\frac{K}{f}}$$

where θ is the contact angle which the wetting fluid makes with the rock surface. With gas-liquid systems of the usual type, the liquid almost completely wets the rock interstitial surface; hence $\cos\theta$ is very nearly 1.

The term $j(S_w)$ denotes a dimensionless function that varies with the water saturation. P_c is the capillary pressure at the same water saturation. It is found experimentally that the plot of $j(S_w)$ *vs.* S_w is very nearly the same for two samples of the same kind of rock, even though the porosity and permeability may differ. The curves shown in Fig. 8 each apply to several samples of different permeability and porosity. Thus the "Hawkins" curve applies to several different samples of

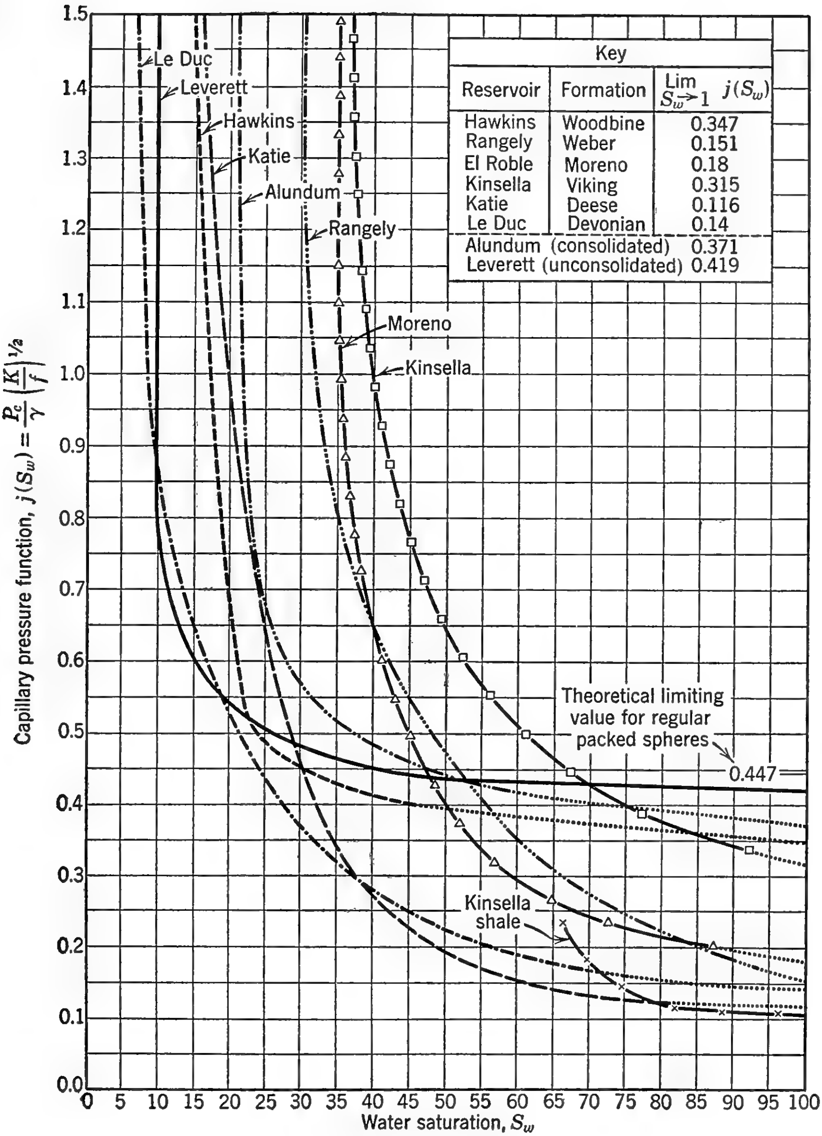

FIG. 8. Capillary pressure function $j\ (S_w)$ *vs.* saturation. (After Rose and Bruce, 1949, p. 134.)

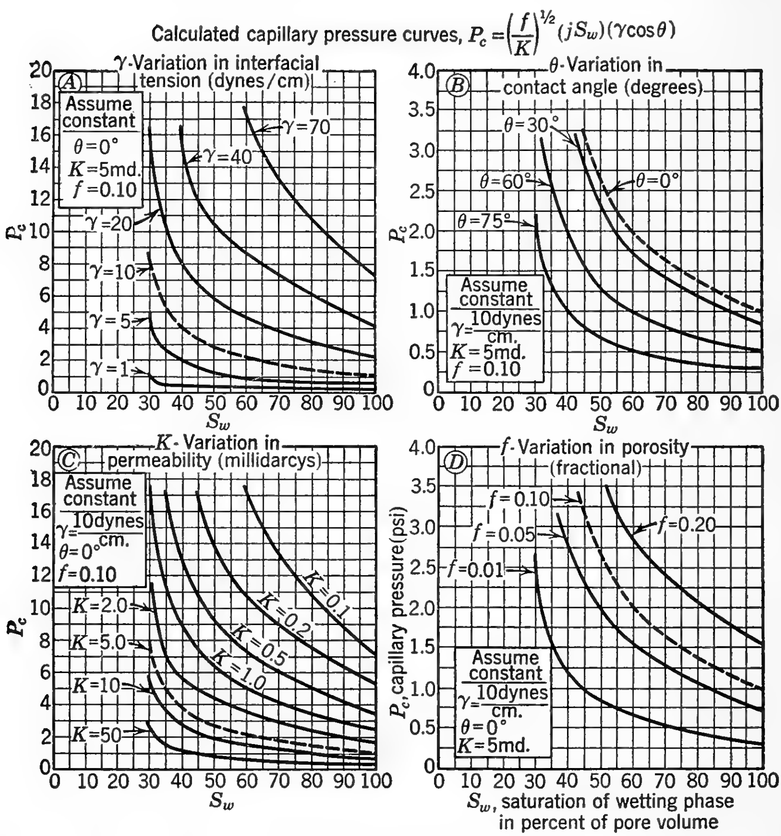

FIG. 9. Effect of different interfacial tensions, contact angles, permeabilities, and porosities on the capillary pressure-water saturation curve. (After Rose and Bruce, 1949, p. 131.)

Woodbine sand from the Hawkins pool, with permeabilities between 2,000 and 6,000 millidarcys, while "Rangely" applies to several samples of Weber sand with permeabilities ranging from 1 to 10 millidarcys. Each of these samples has its own distinct capillary pressure-saturation curve. When the j function is calculated for each capillary pressure and plotted against the water saturation at that pressure, it is found that all samples of the same rock give nearly identical curves, but that curves of different rocks are different. The authors point out that this suggests very strongly that each reservoir rock is characterized by some particular texture which persists through variations in grain size. Apparently this constant factor is expressed by the square root of the porosity divided by the permeability.

Through the use of this j function, it is easy to study the effect of variations in interfacial tension, contact angle, permeability, and porosity on the capillary pressure-saturation curve, as shown in Fig. 9. In making this diagram, these authors have kept all the parameters in the j function constant, except one which was allowed to vary.

Surface Area

In any review of porosity, permeability, and capillarity, it is necessary to treat the subject of interstitial surface area, or, in other words, the exposed surface of the void space in the porous medium. According to Carman (1937, 1948) and Kozeny (1927), this interstitial surface area is related to porosity and permeability by the equation

$$K = \frac{f^3}{k_0 A^2}$$

where K is permeability, f the fractional porosity, A the specific interstitial surface area (that is, the interstitial surface area per unit of bulk volume), and k_0 is a constant depending on the packing of the material and the tortuosity of the pores. For unconsolidated sand beds of very nearly spherical particles, k_0 is about 5. For a bundle of uniform-sized capillary tubes, k_0 is equal to 2. The Kozeny-Carman equation has been tested experimentally for unconsolidated media. Carman (1941) gives the conditions under which this law is valid. In summary, they are: (*a*) no pores are sealed off; (*b*) pores are distributed at random; (*c*) pores are reasonably uniform in size; (*d*) porosity is not too high; (*e*) diffusion and surface effects are absent.

Some discussion of these conditions is warranted. Condition (*a*) is obvious as sealed-off pores do not contribute surface area for fluid flow but are part of the total porosity of the medium. In this case, however, an approximation to the above law can be written as

$$K = \frac{(f - f_0)^3}{k_0(A - A_0)^2}$$

where f_0 is the porosity associated with the sealed-off pores and A_0 is the specific surface area associated with the sealed-off pore space. With regard to condition (*b*) it is quite possible that the law may be inapplicable to stratified materials such as sandstone, which exhibits a permeability anisotropy; that is, it has a greater permeability parallel to the bedding plane than across it. As a practical example, many samples of oil sand contain parallel shale streaks. The permeability parallel to these streaks is often many times that perpendicular to these streaks. On an experimental or laboratory scale it is often possible to choose the size and boundaries of the system so as to minimize this effect. The sample might be chosen so small as to eliminate the shale streaks or so large that the streaks that cause heterogeneity give rise to a statistical homogeneity. In other words, the sample may be so heterogeneous that it behaves statistically as a homogeneous system.

Condition (*c*), of course, refers also to a statistical average. For a porous medium containing a mixture of large and small pores, more or less equivalent to large and small capillaries in parallel, there exists a higher permeability than if the same porosity is distributed uniformly. The average pore size obtained from flow calculations is really nearer the size of the larger pores than the true average. Carman states that a very wide range of pore sizes in an unconsolidated bed makes it difficult to avoid segregation into layers of different size distribution. Segregation is merely non-random distribution, and in a consolidated medium it would tend to cause a high permeability in a direction parallel to the stratification.

The Kozeny-Carman equation breaks down when the porosity f is greater than 0.8. This effect was studied extensively by Sullivan (1941) for fibers. He shows that k_0 ceases to be constant but increases rapidly with f at high porosities. It is thus probable that the law does not hold in a clay containing as much as 75 percent water. Such a system also affects condition (*e*). In this case it is probable that a portion of the pore water is stationary, that is, chemically bound to the clay surface. In fact, the actual surface over which fluid flow takes place is difficult to ascertain.

The problem of capillary rise in a porous medium was also treated by Carman (1941). For a capillary tube, or a bundle of uniform-sized capillaries, the height of capillary rise h is

$$h = \frac{2\gamma \cos \theta}{rg\rho}$$

where γ is the surface tension, r the radius of the capillary, θ the contact angle, g the gravitational constant, and ρ the density of the liquid rising in the capillary system. In non-circular capillaries and in porous media, r is sometimes replaced by $2m$, the quantity m being the mean hydraulic radius:

$$m = \frac{\text{pore volume}}{\text{interstitial surface area}}$$

or

$$m = \frac{f}{A}$$

This concept of capillary rise is in error for porous media, because water moves into a porous structure without completely filling the pores. Thus the measurement of the capillary rise, that is, the height to which water will fill the pores, is uncertain.

It should be mentioned that the Kozeny-Carman law as stated above has been formulated for the flow of one fluid through a homogeneous porous medium. When two fluids occupy the pore spaces in a sand bed, the situation is much more complex. One way to treat the problem is to consider one fluid moving through a matrix having an interstitial surface made up partly of rock and partly of the other fluid. This is very difficult to treat, and only very limited approximations for the amounts of rock and fluid surfaces can be made. Some attempt to study this problem was made by Rose and Bruce (1949), but the treatment proposed by them is acknowledged to be only very approximate. It is felt that the clue to a statistical description of relative permeability phenomena lies in understanding the Kozeny-Carman law and correlating it with the other physical laws governing the flow of fluids through porous media.

The above discussion has dealt with the relationship of interstitial surface area to permeability and to porosity. Actually, by measuring permeability and porosity of a porous medium of known texture, it is often possible to make an approximate calculation of the interstitial surface area. The several methods for measuring interstitial surface area are discussed in detail by Brunauer (1943). Perhaps the most commonly used is the Brunauer, Emmett, and Teller method, which involves the adsorption of a monomolecular layer of gas on the interstitial surface of the porous medium. If the number of molecules on the surface and the area occupied by one molecule are known, it is possible to calculate the interstitial surface.

SEDIMENTARY FACTORS AFFECTING RESERVOIR PROPERTIES

Nearly all the theoretical and much of the experimental work on the behavior of fluids in porous media has been based on the idealized concept of packed spheres. The experimental data given above show that natural reservoir rocks depart considerably from this ideal. The less consolidated sands, such as the Woodbine (Upper Cretaceous), approach it most closely, while the hard, calcareous Weber (Pennsylvanian) diverges widely. The divergences are caused by petrographic textures in the rocks that make the pores very different from the interstices between spheres.

Gross Dimensions of the Reservoirs

It was once generally believed that the normal hydrostatic pressures encountered within the reservoir when it is first tapped by the drill were maintained by meteoric water percolating down from the outcrop. The behavior of a great many pools, however, shows that there is seldom continuity through the aquifer, or water-bearing portion of the porous reservoir, to the outcrop (Bugbee, 1943). Oil occurs very commonly in sands of limited lateral extent. Even wide, sheet-like sands are generally interrupted by faults, if not stratigraphic discontinuities, between the pool and the outcrop. It appears that the enclosing strata, although they are impermeable to oil and gas, have a small but finite permeability to water. Thus, as the overburden is slowly increased by sedimentation or removed by erosion, normal hydrostatic pressure is maintained in the system by the addition or withdrawal of small amounts of water.

Bedding

Beds and laminae of shale, or even very thin micaceous partings, greatly reduce the permeability of a sand body to fluids. These laminae impede the flow in any direction not parallel to the bedding in nearly all sandstone reservoirs. In the process of water-flooding by the injection of water into input wells, the behavior of the producing wells strongly indicates that a sand body acts like a large number of small, independent reservoirs of differing permeability. The most permeable bed is flushed of its oil and starts to produce water, and then the other units successively produce oil followed by water. The least permeable beds may produce oil 15 or 20 years after the more permeable strata are flushed.

Appreciable permeability normal to the bedding is more common in limestone than in sandstone reservoirs. Fractured and cavernous zones generally occur as stratigraphic units, but the fractures and caverns themselves may transect the bedding planes. In certain pools in Mexico, west Texas, and the Middle East, the oil occupies large open caverns or fractures underground. Certain oolitic lime pools also have high vertical permeability. Among these are the Smackover pools of Arkansas, where water is being injected at a point lower than the lowest oil saturation. The water is apparently advancing upward from under the oil in the center of the pool, as well as laterally from the margins (Horner and Snow, 1943).

Permeability may also vary in different directions in a horizontal plane parallel to the bedding. When gas is injected into a well in order to maintain pressure in a reservoir, it usually appears in greater quantity in one offset well than in the others. Often it may skip the offset wells and appear at a well two or three locations distant. Even small core samples may exhibit perferential permeability in one direction (Johnson and Hughes, 1948).

Grain Size

Slichter showed that porosity is independent of the actual size of the grains but dependent on the uniformity of grain size and the manner of packing. Tickell, Mechem, and McCurdy (1933) investigated the effect of uniformity of grain size on porosity. The porosity decreased as the number of different sizes of particles increased. These authors also investigated the effect of angularity of the particles.

Slichter believed, on theoretical grounds, that the permeability should increase with the square of the grain diameter. Muskat (1937) and later Hubbert (1940) showed that the constant of proportionality in Darcy's law includes a size factor d^2 that expresses the pore diameter, which should be related to the grain diameter for unconsolidated sands. Natural sandstones, however, contain a wide range of grain sizes, and some mathematical method of expressing the distribution of grain sizes must be employed.

Krumbein (1938) suggested that the diameter of the particles be expressed logarithmically in "phi" units, where $\phi = -\log_2 \xi$, and ξ is the diameter of the particle in millimeters. When the grain diameter is expressed in phi units, the grain-size distribution of natural sands can be plotted as a frequency curve which has the attributes of the normal Gaussian curve of mathematical statistics. From such curves the "mean" or center of gravity of the distribution, and the "standard deviation," which expresses the range of particle sizes, can be determined. The standard deviation is the spread in diameters, expressed by Krumbein in phi units, within which 68.2 percent of the particles fall. Otto (1939) adapted logarithmic probability paper for plotting grain-size distribution curves and developed graphical methods of obtaining the statistical parameters.

Krumbein and Monk (1942) investigated the effect of grain size and grain-size distribution on permeability, holding all other factors constant. They used glacial outwash sand, screened into 24 different sizes. These sizes were than recombined in such proportions that they fitted normal probability curves of predetermined mean and standard deviation. The porosity in all tests was 40 ± 0.5 percent. Figure 10 shows the relation between permeability and mean diameter, and Figure 11

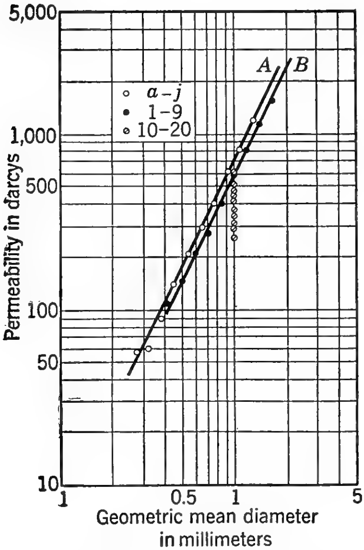

FIG. 10. Effect of mean grain size on permeability of unconsolidated sand. (After Krumbein and Monk, 1943, p. 159.)

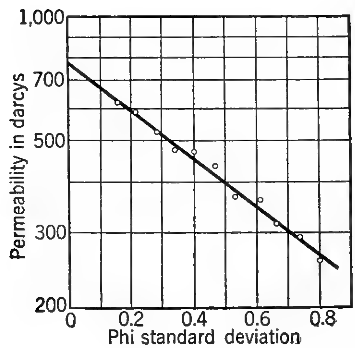

FIG. 11. Permeability as a function of the logarithmic standard deviation. (After Krumbein and Monk, 1943, p. 160.)

the relation between permeability and the standard deviation as a measure of sorting. All the sands plotted on curve *A* (Fig. 10) had a standard deviation of 0.04 phi units, and the mean size varied between 0.273 and 1.30 millimeters. The permeability varied from 57 to 1,195 darcys. Those in curve *B* had a standard deviation of 0.21 phi units. The wider particle-size distribution resulted in a somewhat lower permeability for the same mean grain size. The points on the vertical line represent sands having the same mean grain size, 1.0 millimeter, but standard deviations ranging from 0.15 to 0.80. The curves show that the permeability is proportional to the square of the geometric mean diameter and the negative exponential of the logarithmic standard deviation.

Although these experiments form a very important contribution to theory, the permeability of natural sands cannot be calculated from the statistical parameters derived from the grain-size-distribution curve. Most natural sands have smaller and variable porosity and contain varying amounts of clay and interstitial cement, which have a profound effect on permeability.

Packing

As pointed out by Slichter, the manner of packing of the grains affects permeability and porosity, but very little experimental work has been done to evaluate it. Fraser (1935) found that natural beach sands have porosities ranging from 38 to 46 percent. The variation is due, at least in part, to differences in the manner of deposition. The manner of packing is changed by the compaction resulting from the pressure of overlying strata. Tickell, Mechem, and McCurdy (1933) reduced porosity about 3 percent by compaction under pressures up to about 400 pounds per square inch.

In general, sands in regions where the rocks are highly consolidated show lower porosity than those in areas where the section has suffered less compaction. Thus in the Appalachian Basin the average porosity of oil-producing sands is between 15 and 20 percent, in the Mid-Continent area between 20 and 25 percent, and in the Gulf Coast area between 25 and 30 percent. However, this reduction in porosity with age and depth of burial is probably due much less to the physical rearrangement of grains under overburden pressure than to secondary cementation. At any one locality there appears to be no regular and consistent decrease in porosity with depth in sandstones, although there is such a relation for shales that are more susceptible to compaction.

Clay Content

The porosity and permeability of sandstones are both greatly affected by the amount of clay deposited with the sand grains. Very little analytical work has been done to determine the effect of clay content on porosity, permeability and capillary properties, but the wide variations of these properties are more likely due to the presence of clay and cement than to the grain size and shape, whose relations have been reported.

The porosities of oil-producing sands generally range between 10 and 30 percent. In any particular pool, the porosity ranges from a maximum down to a low value in the shaly layers. The clay may be present as thin laminae of shale, or interspersed generally between the sand grains. Much of the clay firmly adheres to the sand, so that ordinary methods of mechanical analysis may report less clay than is actually present. During compaction the interstitial clay is protected from pressure by the bridging and arching of the sand grains. Consequently it may have a porosity in excess of 50 percent. A small amount of clay may, therefore, have only a small effect on the porosity.

The effect of clay on permeability, on the other hand, is large. The fine clay particles surround the sand grains and reduce the effective diameter of the pores. The presence of a comparatively small percent of clay by weight might have little effect in reducing porosity but a large effect in reducing permeability.

Because of the smallness and platy character of the clay particles, their surface area is large and pore diameter small. It takes, therefore, a very high capillary pressure to displace water from the clay in a sand. Consequently the connate water content of shaly sands is high, often in excess of 50 percent. Some such sands may contain more than 50 percent water and yet produce clean oil, because the water is retained by the clays. This water was probably never displaced during the original accumulation of oil in the reservoir. Figure 6 shows capillary-pressure curves characteristic of low and high clay content.

Most interstitial clay appears to belong to the group of clay minerals called illite or hydromica. The clay particles have a great affinity for water, and they swell considerably when wet. Montmorillonite, which also occurs, has still greater swelling properties. Clays are also sensitive to the salt content and hydrogen-ion concentration of the water in contact with them. Thus if clay is suspended in fresh water of pH 8 or 9, the addition of acid or strong salt water will cause a flocculation and precipitation of agglomerates of particles (Baver, 1948). The introduction of fresh water into a sand in which the clay minerals had been in contact with salt water causes them to swell and reduce the permeability of the sand (Johnston *et al.*, 1945; Breston and Johnson, 1945). The introduction of fresh water into oil sands occurs frequently on a small scale during the drilling and completion of a well. There is some evidence that the productivity of the well may be adversely affected by the plugging effect of the water that filters from the drilling mud. Drilling with mud containing oil as a fluid base is commonly practiced to avoid this effect. It has also been shown that salt water is preferable to fresh water for large-scale injection into sands to displace the oil.

The presence of sufficient clay in sandstones to reduce their permeability to very low values is, perhaps, more common than has generally been realized. By no means are all sandstones sufficiently permeable to produce fluids, even though they may contain them under pressure. A comparatively small percent of clay by weight can raise the capillary pressure to a point where little or no oil could have displaced the connate water originally present. There is some reason to believe that a rather special depositional environment is required to "winnow" the clay from the sand and provide a good reservoir for oil.

CEMENTATION

Most consolidated sandstones contain varying amounts of cement, composed mainly of carbonates and silica, and less commonly of oxides and other minerals. The cement may have been deposited contemporaneously with the sand, or it may have been introduced later during the process of compaction.

Certain types of sandstones, notably the Ordovician sands of the St. Peter type in the central and eastern United States and the Tensleep of the Rocky Mountains, were deposited in association with limestone and dolomite. They grade, both laterally and vertically, into sandy limestone. The amount of carbonate thus varies greatly; in some places the rock is pure quartz sand, whereas in others it is 50 percent or more calcite or dolomite. The porosity and permeability vary accordingly. Occasionally the calcareous sandstone has been subjected to erosion and leaching, resulting in a very soft, permeable sand. When reburied under an impervious caprock, as at Oklahoma City, such sands form prolific oil reservoirs.

Calcite cement is also very common in the absence of limestones and dolomites in the section. Oil very commonly occurs in an alternating sequence of gray and dark-gray shale, and thin sandstones and siltstones. As a rule the top and bottom of the sands are tightly cemented by calcite, the central portion alone being permeable. Completely impermeable calcareous siltstones are common. In these it is possible that the calcite was introduced after deposition by circulating waters expelled from the adjacent shales during their compaction. The presence of oil in the coarser parts of the sand may have so reduced their permeability to water that they were not cemented as much as the finer parts.

Secondary silica cement is also very common in consolidated oil-producing sands. Each grain is frequently coated with a layer of quartz, in optical continuity with the original grain. The deposition of silica apparently begins in the finer interstices and spreads into the larger openings. Thus the finer pores are filled, and the points of contact of the original grains are broadened. The new surfaces bounding the larger pores are frequently plane crystal faces. It appears to be possible (although not yet demonstrated experimentally) that the deposition of secondary silica may reduce the porosity considerably and the permeability only slightly by comparison, because the finer and less permeable pores are filled in preference to the larger and more permeable ones. This contrasts with the effect of clay, where it is expected (but also not demonstrated) that the permeability may be reduced more than the porosity. The coalescence of the grains with the retention of the larger pore openings may result in a hard quartzite with considerable permeability. The texture and pore pattern of such a rock bears little resemblance to those of packed spheres, or even to those of a clean unconsolidated sand.

POROSITY OF SHALES

Fine silts and clays settled out of still water have a porosity greater than 75 percent (Hedberg, 1926), the porosity increasing as the grain size decreases (Trask, 1931). The fine and platy character of the clay particles causes them to settle into a sort of open lattice or cellular structure. As the pressure of the superincumbent sediments increases with continued deposition, compaction occurs by the collapsing of the cells and the expulsion of the interstitial water. There is thus a continual decrease in the volume and porosity of argillaceous sediments as the weight of the overburden increases.

Soft clays have a high porosity but very low permeability, so that the water is expelled slowly. The addition of an increment of overburden results in the partial collapse in the structure of the solids. As the interstitial water cannot immediately escape, it assumes part of the load, which causes an excess pressure in the water above the normal hydrostatic pressure for its depth (Terzaghi, 1943). A pressure gradient then exists which causes the water to filter slowly to regions of lower excess pressure. During the early stages of compaction most of the water is expelled upward. As compaction proceeds, however, the permeability in a vertical direction is reduced more than that in a horizontal direction. This is due partly to the flattening down of the platy clay and micaceous particles and partly to the existence of more permeable sandy layers that may extend considerable distances in a horizontal direction. There are thus numerous paths of migration, with different lengths and permeabilities, by which the water may flow to zones of lower excess pressure. The water will distribute its flow in proportion to the relative resistance of the various paths. Some of it will therefore move long distances parallel to the bedding, and some may actually move downward a short distance to reach a permeable layer. During compaction, therefore, there exists a component of water flow in a lateral direction toward areas of less rapid sedimentation. Occasionally pools are found in which the pressure in the fluids may be considerably above the normal hydrostatic pressure at their depth, as in certain reservoirs in the Texas Gulf Coast. It is possible that the rate of sedimentation was especially fast, and that the clays were especially impermeable, so that it has taken the water a long time to be expelled.

When the pressure in the fluids in a sand reservoir is lowered to much less than normal hydrostatic, a pressure gradient between the reservoir and the adjacent shales is set up. This gradient causes a slow migration of water from the shale to the sand. A few oil pools, notably Goose Creek, Texas, have shown subsidence of the surface. It has been suggested (Pratt, 1927) that the subsidence is not due to the withdrawal of solid sand particles, but to the local compaction of the shales adjacent to the reservoir resulting from the migration of their interstitial water into the sand.

Although the compaction of shales is most rapid during the early stages, it continues to great depths of burial. Athy (1930) determined the density (which varies inversely with the porosity) of a large number of samples of Pennsylvanian and Permian shales from Oklahoma. The density of these samples plotted against depth is shown in Fig. 12. They show a diminishing rate of increase of density with depth from about 2.2 at 600 feet to 2.6 at 5,000 feet. By extrapolation, it was estimated that a density of 2.2 indicated burial to about 2,000 feet, so that about 1,400 feet of overburden had been removed by erosion in this area. If the density of the mineral grains is 2.7, a dry density of 2.2 indicates a porosity of about 19 percent, and a density of 2.6 indicates a porosity of 4 percent. During burial from 2,000 to 7,000 feet, therefore, more than 1,000 barrels of water was expelled from each acre-foot of shale. During the early stages of compaction much greater quantities are expelled.

The lateral migration of water may be an effective agent in the accumulation of oil. The chemical constitution of the organic matter in the shales is unknown. It is largely insoluble in organic solvents and probably contains oxygen and nitrogen, so that it does not resemble hydrocarbons. If, however, hydrocarbons are formed from this material by catalysis, radioactive bombardment, hydrogenation, or some other mechanism, the moving water may sweep it along (McCoy and Keyte, 1934). The oil droplets will tend to coalesce and segregate in the coarser pore openings in the sands. If the oil is carried along as tiny droplets in a current of water, it will be filtered out at any point where the mean pore radius diminishes. If the water wets the solid surfaces, the oil cannot penetrate pores less than a certain size until the pressure difference across the oil-water interface reaches a certain amount. When this difference is attained by the addition of oil to the column, the oil will penetrate the barrier and rise and accumulate

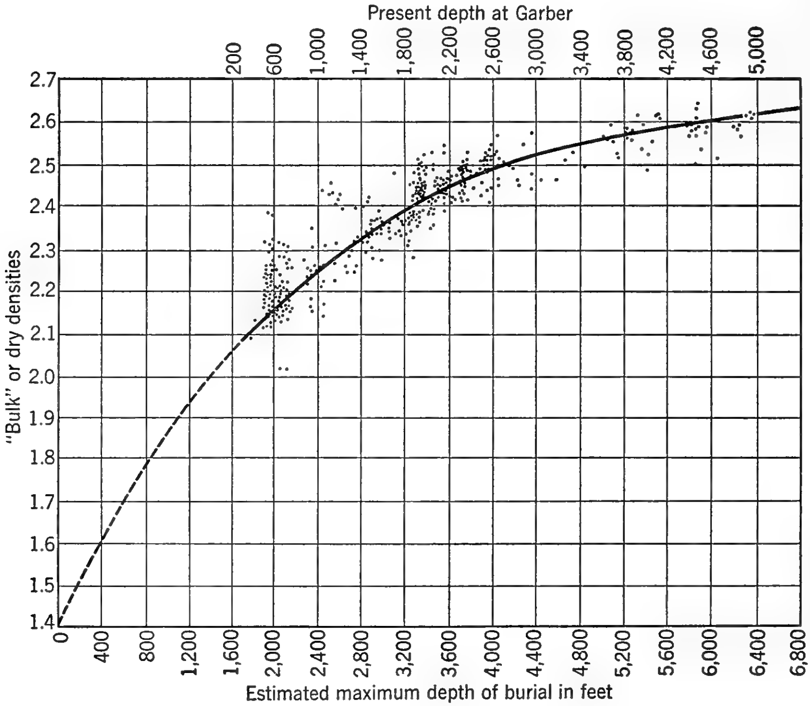

FIG. 12. Change in density of Pennsylvanian and Permian shale with depth of burial in Oklahoma. (After Athy, 1930, p. 12.)

in the uppermost portion of continuous sand bodies. The height of an oil column is seldom or never enough to give rise to a capillary pressure sufficient to penetrate shales or shaly sands; therefore they act as impermeable barriers.

The migration of water as a result of compaction probably accounts also for some of the phenomena of cementation. Anaerobic bacteria that grow in bottom sediments obtain their oxygen from the reduction of sulphates and produce carbon dioxide and hydrogen sulphide. These gases, dissolved in the water, are probably effective in dissolving carbonate and silica and reprecipitating them in zones of lower pressure and temperature.

SUMMARY

It has been pointed out that it is important to understand the behavior of fluids in porous media in order to improve the methods for finding accumulations of oil and for producing the oil when it is found. It is necessary to know what effects in this behavior are caused by variations in both the fluid and rock properties. The way in which the rock is put together and the geometric configuration of the pore spaces, as well as the chemical nature of the interstitial surfaces, control the movements of oil, gas, and water during their original accumulation and also during oil-production operations. Although many of the basic principles of the behavior of fluids in porous media have been established, much experimental and theoretical work remains yet to be done. There has been very little investigation of the processes of sedimentation and diagenesis in determining the amount and nature of porosity in sediments.

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Chapter 33

CARBONATE POROSITY AND PERMEABILITY

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STATEMENT OF PROBLEM

The petroleum industry's main interest in carbonate rocks is in the formation of porosity and permeability. Many dolomites and limestones contain liquid hydrocarbons; however, the porosity or permeability factors are frequently so low that it is not economically possible to produce the contained fluids or gases. The industry has developed techniques of increasing porosity and permeability; however, only a relatively small amount of fundamental research has been undertaken in the mechanics and development of naturally occurring porosity and permeability. The need for systematic research in carbonate porosity becomes more urgent when it is realized that over half of the world's presently known petroleum reserves are contained in carbonate rocks.

For many years the industry has carried on experimentation with and practiced secondary recovery of liquid hydrocarbons from sandstone reservoirs. Employing the motivating force of injected or introduced water, or injection of air or gas into key wells, has resulted in phenomenal recoveries of oil above that produced by natural means with normal reservoir behavior. Repressuring of the oil sands in western Pennsylvania, eastern Illinois, eastern Kansas, and Oklahoma has resulted in the recovery of millions of barrels of oil which would have otherwise been lost to our national petroleum economy. In some of the eastern Kansas secondary recovery projects, more oil will be recovered during the secondary phase of production than was obtained by normal producing practice.

Unfortunately, only a small amount of secondary recovery has been attempted in carbonate reservoirs, and this with varying degrees of success. Natural water-flooding of the McClosky formation in eastern Illinois represents a successful attempt at secondary recovery. Other programs have attained only moderate results, and many have failed completely. Surely carbonate reservoirs hold more trapped oil than sand reservoirs, oil that cannot be produced by primary producing methods. Why, then, have not more attempts been made to repressure the carbonate class of reservoirs? The answer to this question is manifold and complicated, and there is lack of general agreement among geologists and engineers regarding the difficulties of secondary projects in carbonate reservoirs. Basically, most of the difficulty results from a lack of fundamental data pertaining to the formation of carbonate porosity and the character of the resulting rock. Comparatively speaking, determination of the physical aspects of a sandstone reservoir is relatively simple. The thickness of the reservoir can be measured and its lateral extent predicted by determining the area of oil-saturated sand. Differences in effective porosity may be charted by core analyses. Unless a sandstone reservoir has undergone extensive postdepositional change, differences in porosity are mainly of a depositional nature. On the other hand, porosity and permeability in carbonate rocks are largely due to the secondary forces of solution and chemical deposition of moving ground waters. Some porosity is undoubtedly present during early stages of postdeposition; however, there is rather general agreement among geologists that the main change in the nature of porosity in carbonate rocks occurs as a result of secondary forces.

There can be little doubt that new petroleum reserves are becoming more difficult and expensive to find. If our petroleum economy can be improved by recovering "trapped" oil, which would otherwise be lost, we have in effect added important discoveries to our general reserve picture. This field of investigation calls for close cooperation of the chemist, physicist, geologist, and engineer.

DYNAMIC PRINCIPLES INVOLVED

In a study of porosity we are interested in (1) the shape of the openings, (2) size of the openings, and (3) the origin of openings. The size and shape of the openings can be measured and described, but the origin is more complicated because it involves physical and chemical forces which were operative during geological history.

The size of openings in calcareous rocks ranges from subcapillary openings (tubular openings less than 0.0002 millimeter in diameter) through capillary sizes (tubular openings greater than 0.0002 to 0.5

millimeter in diameter) to supercapillary (tubular openings greater than 0.5 millimeter in diameter). Theoretically, the subcapillary openings are not important in the production of oil, because the molecular attraction of the solid for the liquid is so great that the liquid tends to remain in the void. In capillary openings, the contained liquids move slowly and only under hydrostatic force that exceeds the molecular attraction of the liquids for the walls of the opening. Liquids contained in supercapillary openings move freely and obey the ordinary laws of hydrostatics. Therefore it is with the openings of capillary and supercapillary size that we are primarily concerned.

The shapes of openings in calcareous rocks are many and varied. Some are tabular or sheet-like, as for example the space between cleavage surfaces of crystals, joints, and fractures. Other openings may be spherical or ellipsoidal as shown by the common pinpoint porosity, where the voids are due to the removal of oolites by solution, giving rise to oolicastic-type porosity. Under certain conditions much of the cementing material around the oolites is removed by solution to produce a carbonate rock composed of spherical oolites whose porosity does not differ too greatly from that exhibited by a well-rounded sand in sandstone. In some oolitic rock there is strong evidence that the void space between the oolites has never been filled by cementing material, and the resulting rock is comparable to a sandstone in its manner of deposition. The solution of fossils such as ostracods, fusulinids, brachiopods, or gastropods creates openings that represent molds of these remains. Very often openings found in limestones or dolomites are extremely irregular in shape and may be described as cellular in character.

In some instances, the origin of the resulting porosity can be read from the shape of the openings; however, the secondary forces of solution frequently alter the original openings to such an extent that the primary characteristics are lost.

In studying the formation and development of porosity, it is convenient to consider it in terms of origin or primary character and of the changes that have taken place as a result of secondary forces. Primary porosity consists of those openings formed at the time of deposition of the rock or shortly thereafter at the time of lithification. Such primary openings may also be formed long after rock deposition as a result of various earth movements which produce faulting, jointing, and fracturing. Essentially, secondary porosity is produced by chemical solution of the rock, or deposition, molecule by molecule, of soluble salts in existing voids.

Openings of a primary character are voids between individual crystals and between cleavage planes of crystals. Certain sedimentary rocks such as breccias, conglomerates, coquinas, and oolitic rocks have primary porosity owing to the character of the material deposited. Differences in crystal size and arrangement along bedding planes may result in another type of primary openings. Earth movements resulting in faults, fractures, and joints produce still another type of void which is considered primary in origin.

The examination of a piece of porous limestone or dolomite seldom permits reading of its geological history. This is due to its having been subjected many times to agents possessing the power to alter the porosity by solution or deposition. The basic factor to be held in mind is that porosities as we now find them are undoubtedly the results of secondary alteration of one or more of the types of recognized original porosity. Joints, fractures, and bedding planes furnish channels that make it possible for ground water to move rapidly, bringing about such alteration as it is capable of rendering.

Secondary porosity is thought to be formed mainly by the dissolving power of connate or meteoric waters containing small concentrations of carbonic, organic, or sulphuric acid. Such waters have an amazing power to dissolve calcareous rocks if the movement of the water is sufficient to keep the water undersaturated. It is believed that most of the solution takes place above the ground-water table, where solutions tend to be acid in character. Below the ground-water table, solutions are usually more alkaline and become more nearly saturated; therefore there is a normal tendency for carbonate precipitation at this horizon. On the other hand, if the ground water moves with sufficient rapidity, it may reach the water-table level with adequate dissolving power to continue its work as it moves laterally. Interbedded shales or those adjacent to carbonate rocks often contain considerable quantities of carbonaceous material, both animal and vegetable, which was not entirely oxidized before burial. This material in its present state of preservation undoubtedly involved a release of considerable carbon dioxide which was available to combine and form carbonic acid. By this process, solution of carbonate rocks could be accomplished well below the ground-water table.

Many porous carbonate rocks show evidence of both solution and deposition. Presumably much of this development could have taken place almost simultaneously, so that the solutions were at a point of being slightly undersaturated at one moment with power to dissolve and slightly oversaturated at another moment with resulting deposition. The process of solution and deposition has taken place many times during geologic time as a result of mountain building, erosion, and submergence. Generally speaking, better carbonate porosity is found in regions where there has been considerable tectonic activity.

PRACTICAL APPLICATIONS

As pointed out earlier in this treatment of carbonate porosity, relatively few programs of secondary recovery in calcareous rocks have been undertaken. The apparent lack of active interest in repressuring carbonate reservoirs undoubtedly may be attributed to the lack of success attained in those projects already undertaken. Figures are not available from which the total number of failures can be counted. Assumptions are dangerous, but in this instance it is safe to assume that the majority of attempts have ended in failure or have achieved only moderate success. Such a record certainly does not encourage continued attempts at carbonate reservoir repressuring.

Most of the difficulty experienced is thought to be due to a lack of fundamental data bearing on the nature of the porosity and the manner in which it was formed. Seldom are data available, on the older carbonate reservoirs, or for that matter on the more recently developed reservoirs, that will permit the engineer to predict the character of flow of fluids or gases through the voids. Of equal importance is the determination of optimum rates of flow through these porous media. Certain repressuring agents are better adapted to some types of porosity than they are to others. All these considerations are important to the engineer when he is considering the feasibility of secondary recovery from carbonate reservoirs.

Reservoir mechanics is an involved study of reservoir behavior under different producing conditions. In a sandstone reservoir the optimum rate of fluid movement can be determined readily because of more nearly uniform porosity and permeability. In carbonate rocks there is wide variation in the reservoir index of porosity and permeability which makes it difficult to handle the fluids in the most efficient manner. At least 10 percent less oil is produced naturally from carbonate reservoirs than from the average sandstone reservoir where conditions of porosity, saturation, and character of the fluid are comparable.

Often the average carbonate reservoir is produced at a rate too high to permit the most efficient "sweeping" of the reservoir oil. This is particularly true of those reservoirs under an active water drive. Owing to great differences of porosity and permeability within the limestone or dolomite, some of the fluid passes along fractures and crevices at high velocity. Other fluid held in less porous or less permeable rock has difficulty getting into the "stream." For this reason, much oil still remains locked in voids after the flush production is gone.

Many of the early Permian fields of west Texas are now producing up to 95 percent water on the pump. Eventually the water percentage will increase until it is no longer economically feasible to operate such wells. The oil now being produced from these fields represents fluid that was "by-passed" during the flush stage of production. Would it not be better conservation and operation to produce the flush oil at a slower rate and in so doing reduce the tremendous amount of water handled in the final "sweeping" process?

Frequently acid is introduced into limestone and dolomite reservoirs to improve the existing porosity and permeability. The benefits of such treatment are attested by performance data before and after acid treatment. It is not unusual to find a well that does not respond normally to treatment. Repeated applications of thousands of gallons of acid seem to produce few, if any, results. In such instances, considerable difficulty is experienced in getting the acid into the formation and in recovering the spent or residue acid.

Selective acidization has to some extent aided in reducing the frequency of "problem wells" and has materially improved the performance of normal treatments. Selective treatment is possible only when something is known about the amount, character, and location of the porosity and permeability in the reservoir to be treated. Each well drilled into a carbonate reservoir exhibits different rock characteristics that call for special consideration. A porosity-permeability log is a part of good operation and should become routine practice.

The geologist and the engineer can contribute much to a better understanding of carbonate rocks if they will recognize the problem and then do something to improve our knowledge of the subject. This can be done by individual effort or through the work of others. Geologists and engineers working with the carbonate group of rocks should be quite frank regarding our lack of fundamental data and should give wide publicity to the problems confronting the industry. Much good work may be accomplished in universities by graduate students working on the manifold problems as thesis material. Commercial research organizations are capable of contributing much worth-while data. Many large oil companies have laboratories completely equipped with the latest type of equipment, and those who are in a position to formulate research projects should attempt to supplement our information by continuing carbonate research effort.

FUTURE NEEDED RESEARCH

The following suggested research approaches to carbonate porosity are not intended to be a complete list. The more obvious and better known techniques are mentioned as a start on the problem with the full realization that other useful approaches are not mentioned.

INVESTIGATION OF MINERAL AND ROCK PROPERTIES

Spectrographic analysis. The identification of minor mineral constituents is readily accomplished by the emission spectrograph and flame photometer. Such equipment is expensive and requires considerable time to set up; however, once the elements to be determined are grouped, the method is rapid, effective, and relatively inexpensive.

Petrographic methods. The ordinary petrographic microscope may be employed, crushed grains, polished surfaces, and thin sections being used. Staining and etching techniques as well as methods based on optical properties offer interesting approaches to the general study.

Thermal analysis. A rapid and accurate method of mineral identification is available through thermal studies. This technique may be applied to carbonate rocks to determine their mineralogical composition.

Electron micrography. The possible use of the electron microscope should be investigated; however, new techniques will probably have to be developed to adapt this method to mineral identification. The method will probably find more utility in studies of the details of orientation and distribution which could furnish direct application to studies of chert and development of porosity.

Heavy liquids and centrifuge. Mineral separation can be accomplished by simple gravity differentiation through the use of heavy liquids or the centrifuge.

Quantitative chemical analysis. Chemical analyses are expensive, and they find limited use as a check against other more rapid and less costly methods.

Insoluble residues. A large variety of substances, both mineral and organic, are relatively insoluble in dilute hydrochloric acid. The insoluble residue consists mainly of chert, opal, clay, silt, and sand, with non-mineral organic constituents in recognizable amounts. In all probability, clays are partly altered or destroyed in residue preparations; nevertheless some value may be gained from their investigation, and this should certainly be included in a general program. Most insoluble residue work has been done to expedite stratigraphic correlation in carbonate rock. We should not lose sight of the possible value of impurities to determine distribution and orientation, which may have important implications in the development of porosity and permeability.

Clastic carbonates. There is growing recognition of the part that clastic carbonates play in the composition of many limestones and dolomites. The action of circulating ground waters and the resulting development of porosity will obviously follow patterns in fragmental rocks different from those in more uniform chemical or biochemical precipitates. Petrofabric investigation could be expected to show relationship of grain size to porosity, cementation, and other phenomena related to the development of porosity and permeability.

Character and Formation of Porosity and Permeability in Carbonate Rocks

A broad investigation of the formation and development of porosity and permeability will employ many of the foregoing techniques. Much has been written about changes that take place when a limestone is altered to dolomite or dolomitic limestone. More consideration should be given to the development of porosity in dolomites deposited as dolomites. A searching study of the paragenetic history of carbonate deposition is an essential approach to the problem. Equally important is a thorough investigation of the increase or destruction of porosity by chemical solution or precipitation.

Minor quantities of anhydrite, salt, and gypsum are found in frequent association with carbonate rocks. Such minerals are dissolved more readily, even in non-acidic waters, than are limestone and dolomite. The resulting vug holes and ribbon-like channels provide ready passage for ground waters to improve the existing porosity.

The terms primary porosity and secondary porosity should be avoided because of the difficulty of definition. It is generally recognized that certain rocks are both porous and permeable when deposited and remain so during and after lithification. More investigations should be made of the changes that take place in original porosity and permeability as a result of solution and deposition.

Three methods are especially well-adapted to the study of porosity formation and the geological processes involved.

(1) Petrographic study of thin and polished sections and the use of staining and etching techniques is a basic approach to the establishment of the geologic history of changes that have taken place within

the reservoir as a result of the action of ground waters on previously existing porosity and permeability. Determination of crystal size, composition, and arrangement should furnish important data regarding the relationship of the porosity to present conditions in the rock and to the sequence of events during the geologic past.

(2) Standardized techniques of core analysis give dependable values for the simple gross quantities of porosity and permeability. Both vertical and horizontal porosity and permeability values should be determined for purposes of correlating experimental data.

(3) A technique of impregnating porous carbonates with a plastic known as Catalin has been developed which produces a faithful cast of the original pore space. Briefly, plastic is impregnated under high pressure into samples of reservoir rock that have first been cleaned and dried. Air is evacuated from the pore spaces, and plastic is forced into the openings. The Catalin polymerizes in about 72 hours at 80° C. After polymerization, the specimen is sectioned and placed in hydrochloric and hydrofluoric acid to digest the carbonates and silicates. The plastic, which is not affected by either acid, remains as a model of the porosity and permeability plus those parts of the original rock not affected by either acid. The resulting mold furnishes a replica of the connected pore spaces, something that can be handled and studied for the geological story it tells. The plastic-model approach promises to be a useful tool in its application to specific reservoir problems and studies when a qualitative answer is desired. It is also possible that quantitative techniques could be developed in the plastic-model method.

The photographs in Figs. 1 through 7 were made of actual plastic models of carbonate rocks collected in west Texas, Oklahoma, and Kansas; they clearly illustrate the effectiveness of plastic impregnation as an aid in telling a geologic story. In the interpretation of these photographs, it is important to remember that the dark areas represent rock mass which was not porous or permeable and therefore did not receive the impregnation of Catalin. The white portion of the picture is Catalin that was forced into the porosity and therefore represents a model of the porosity.

Figures 1 and 2 are examples of intercrystalline-type porosity. Figure 1 is Devonian dolomite from west Texas which suggests development of intercrystalline porosity along a fracture. Figure 2 is a model of Arbuckle intercrystalline porosity from Barton County, Kansas. This model shows no evidence of fracture-controlled porosity but rather an irregular pattern with constrictions between the larger pores.

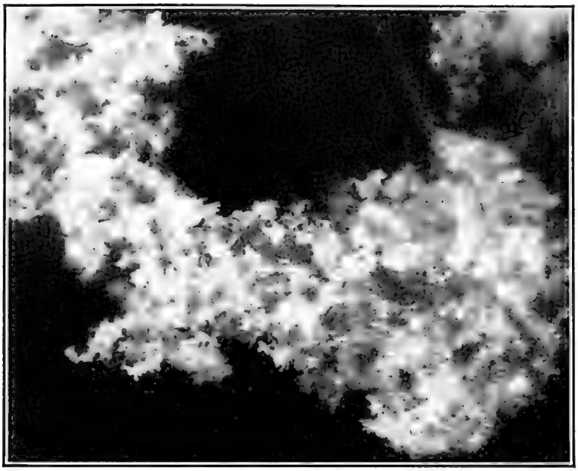

FIG. 1. Plastic model of intercrystalline porosity, seemingly developed along a fracture. Devonian dolomite, South Fullerton Field, Andrews County, Texas. Magnification 10×. (From Imbt and Ellison, 1946, p. 367.)

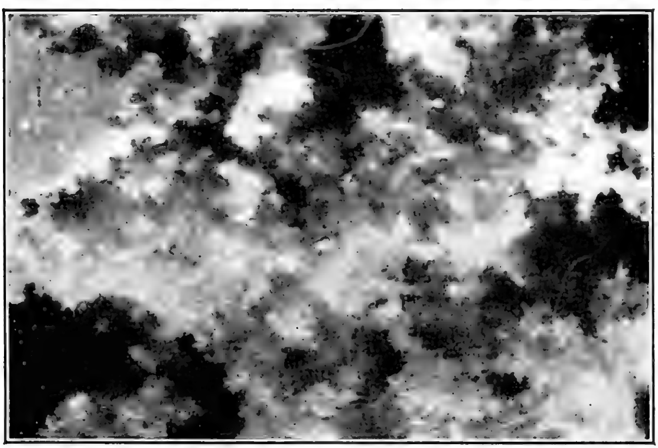

FIG. 2. Plastic model of intercrystalline porosity, apparently due to weathering. Arbuckle limestone (Cambro-Ordovician), Silica Pool, Barton County, Kansas. Magnification 11.6×. (From Imbt and Ellison, 1946, p. 369.)

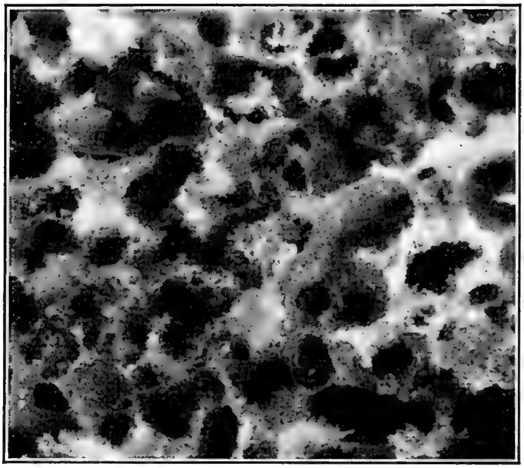

FIG. 3. Plastic model of oolitic porosity. Devonian carbonate rock, South Fullerton Field, Andrews County, Texas. Magnification 10×. (From Imbt and Ellison, 1946, p. 367.)

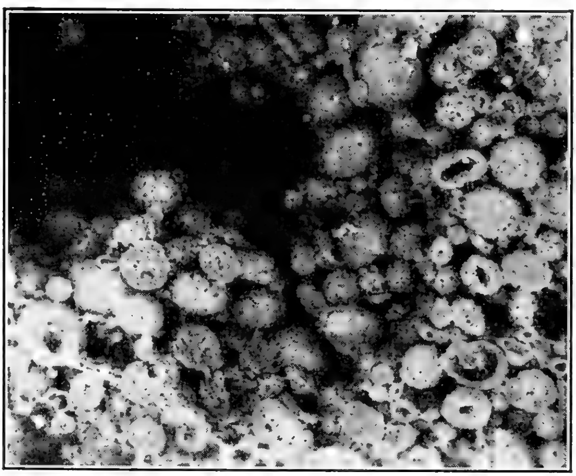

FIG. 4. Plastic model of oolicastic-type porosity. Hunton limestone (Devonian), West Edmond Field, Oklahoma. Magnification 10×. (From Imbt and Ellison, 1946, p. 370.)

FIG. 5. Plastic model of fractured carbonate rock, showing little solution by ground water. Clear Fork formation (Permian), Fullerton Field, Andrews County, Texas. Magnification 10×. (From Imbt and Ellison, 1946, p. 368.)

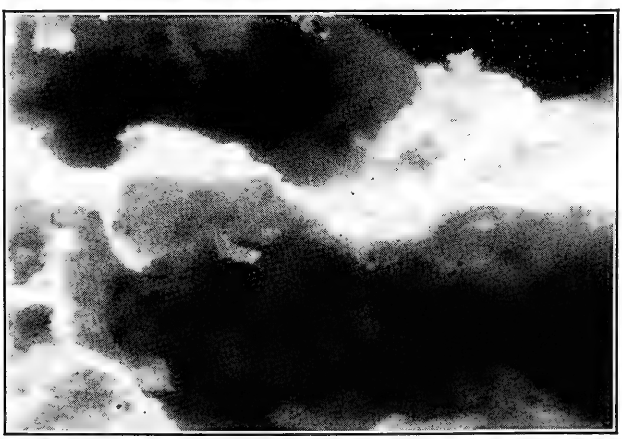

FIG. 6. Plastic model of fractured carbonate rock, showing evidence of solution along a fracture. Clear Fork formation (Permian), North Monahans Field, Winkler County, Texas. Magnification 11.6×. (From Imbt and Ellison, 1946, p. 369.)

This is typical of what one might expect to find in a porosity developed by weathering.

Figures 3 and 4 show plastic models of two different types of oolitic porosity. Figure 3 illustrates typical oolitic porosity, in which the oolites are preserved and the porosity is caused by the void space around oolite in much the same manner as the porosity in a sandstone is formed by the voids between the individual sand grains. Figure 4 illustrates oolicastic-type porosity. In this kind of porosity the in-

FIG. 7. Plastic model of fractured carbonate rock (Devonian), showing secondary ground-water solution. South Fullerton Field, Andrews County, Texas. Magnification 10×. (From Imbt and Ellison, 1946, p. 366.)

dividual oolites are removed by solution, and the resulting rock is actually a mold of the original rock. Generally speaking, oolicastic-type porosity is not so effective as oolitic porosity. Actual core analysis of the rock from which Fig. 3 was prepared shows a porosity of 11.2 percent and a permeability of 2,890 millidarcys. Similar tests on the rock material of Fig. 4 shows a porosity factor of 6.7 percent and a permeability of 2.4 millidarcys. Close inspection of Fig. 4 shows much unconnected porosity that is not effective in permitting the free flow of contained liquids in the reservoir.

Figures 5 through 7 show results of impregnating fractured carbonates with Catalin. Figure 5 illustrates a fracture model where there has been very little solution by ground-water action, although it is suggested that solution laterals are beginning to develop. Figure 6 is still another fracture impregnation showing a ribbon-like pattern, with considerable evidence of solution action which has enlarged and modified the original opening to a large extent. Figure 7 likewise shows the influence of fracturing, but in this instance a large amount of secondary ground-water solution is shown by the lacy pattern of the plastic model. This sequence of pictures effectively illustrates the progressive action of ground-water solution in the improvement of carbonate porosity and permeability.

All three of the preceding suggested methods of study are largely dependent on satisfactory recovery of samples representative of the reservoir bed. The use of conventional coring methods leaves much to be desired, as recoveries are usually not complete and the core loss occurs in the more porous rock. By use of a diamond-studded core head, recoveries approaching 100 percent are now possible in carbonates where the chert content is not too high. Improved design and technique may eventually make it possible to core chert formation with recoveries approaching 100 percent.

THE CHERT PROBLEM

Almost all carbonate rocks contain varying amounts of interbedded primary and secondary chert. Inasmuch as chert is so common in carbonates, we might expect to know more about conditions of carbonate deposition if we were in a position to know the environment in which chert was formed. The deposition of chert is in itself enough of a problem to justify a special program of research; moreover, owing to the intimate association of chert with limestone and dolomite, a program of carbonate research could not be considered complete without investigation of chert in carbonate deposits.

Generally speaking, chert may be formed by (1) chemical precipitation of colloidal silica, (2) the release of silica by bacteria, and (3) deposition from silica-saturated ground waters. Most of the techniques for carbonate research could be equally well employed on the chert problem.

As chert is a very important part of many carbonate rocks, it gives rise to many economic problems. The presence of chert not only adds to the drilling problem, but also sometimes the associated limestones and dolomites do not develop porosity, and it is the fractured chert that actually forms the reservoir.

CARBONATE-FORMATION WATERS

A study of the chemical characteristics of carbonate-reservoir waters should receive attention as part of a well-rounded program of fundamental research regarding the nature and origin of carbonate porosity. Chemical composition and relationship to other geologic phenomena should include both common and uncommon characteristics of carbonate waters, with special emphasis on the measurements of sodium and potassium, also organic acids, if present.

PHYSICAL PROPERTIES OF CARBONATE SURFACES WITH SPECIAL EMPHASIS ON WETTABILITY

The recovery of the maximum amount of oil from a carbonate reservoir depends on a large number of factors, among which conditions of porosity and permeability are important considerations. Of importance also are the physical and chemical make-up of the reservoir rock and the fluid retention characteristics of the reservoir material. The suggested study should consider the "wetting" effect of various reservoir fluids, both oil and water, and also free gas in solution. Equally important in such a study would be experimentation in the reduction of surface tension by introduced chemicals or changes in the physical characteristics of the reservoir rock.

LABORATORY RESEARCH APPLIED TO FIELD PROBLEMS

The ideal coordination of carbonate research would be the application of the suggested procedures to the same reservoir material from a producing field exhibiting as many variables as possible. Thus a more or less complete picture could be formulated from various research approaches. Conditions of carbonate deposition and porosity formation vary widely over short distances even in the same formation. Data that cannot be correlated are of little value to the correct solution of a complicated problem.

A well-organized program of carbonate research should investigate the formation and development of porosity in the recently deposited limestones as a pattern to be extended to the older rocks which have suffered many postdepositional changes. Through a better understanding of the early characteristics of carbonates, we should find ourselves in a better position to unravel the complicated history of the older carbonates.

These research approaches are suggested as methods to be used to correlate chemical and physical characteristics of carbonates to the development of porosity and permeability patterns. From such investigations, it should be possible to predict with reasonable certainty the type of porosity or permeability to be expected under geologic conditions known to be operative in the area.

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Part 7

MILITARY APPLICATIONS

Chapter 34

SEDIMENTARY MATERIALS IN MILITARY GEOLOGY *

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Geology can be profitably utilized in warfare, especially in the fields of military construction and intelligence.

Knowledge of the principles of sedimentation plays an important part in engineer intelligence, whose function is epitomized in the military term "terrain appreciation." The engineer must know in advance the characteristics of the country to be fought over. In the wars of the last century and before, this meant simply a knowledge of the topography of a relatively small battleground; in modern military operations, subsurface conditions must be known because of their influence on military construction and troop movement. It is the duty of the geologist and the soil scientist in military intelligence to deduce the characteristics of subsurface and surface materials in inaccessible areas. He must then determine the uses to which these materials can be put in construction of airfields, roads, and surface and underground installations; their effect on the movement of military vehicles across country in any weather; and their characteristics as sources of water supply. These and other applications of geologic reasoning, accurately and succinctly presented, enable the responsible officers to lay out the battle plan in terms of establishing beachheads and airheads; movement and supply of troops; construction, repair, or extension of airstrips; maintenance of roads; and securing the objective area. Field geologists act in a consulting capacity during and after the operation. It is desirable for geologists to be assigned as consultants on the operations for which they prepared intelligence studies.

APPLICATIONS TO MILITARY INTELLIGENCE AND OPERATIONS

The reasoning used in military geology is the same as that in any form of applied geology. In presenting the results of such reasoning

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to responsible officers it is not, of course, necessary to present the steps by which the conclusions were reached. Almost all terrain-intelligence interpretations are made by deducing, in whole or in part, the geologic history of the area in question. It is in this stage of study that the principles of sedimentation and other basic geologic principles are used. The reasons for not presenting these deductive steps to the military users of the data are obvious: they have neither the time nor the specialized training to examine what, compared to the vast scope of a military operation, are minutiae. The necessity of presenting conclusions therefore places a heavy responsibility on the military geologist. Their reliability will differ widely, depending on how much basic information (geologic reports, maps, aerial photographs) is available. A reliability rating system was used in most military geology reports in World War II.

Because of the factor of expediency in military operations, the tendency has been to define the engineering properties of earth materials qualitatively, not quantitatively. This is illustrated by Table 1, a portion of a larger table prepared by von Bülow (1938).

Terrain Appreciation

In preparing an intelligence report for planning purposes, or in the more detailed work of preoperational intelligence, it is best to learn as much as possible about the entire area involved, even though immediate intelligence needs may apply only to part of it or to one aspect of regional knowledge such as, for instance, location of material for concrete aggregate.

Accordingly it is standard practice in military geology to prepare, first, generalized geology and soils maps of the assigned area and, on the basis of these, to construct a terrain-appreciation map. The latter is best described as an applied physiographic map (Fig. 1). With its accompanying text, it is designed to emphasize important land forms, such as cliffs, steep slopes, and reefs; to summarize ground conditions, bedrock types, and kinds of vegetation; and to inform the reader briefly and clearly of the most feasible corridors for movement and of barriers that will prevent movement; of cover (protection from enemy fire), such as ravines and boulders, and concealment, such as brushy woods or sugar cane. The best points of observation are indicated, and the problems of constructing hasty fortifications pointed out.

The military geologist seldom has a geologic or soils map of the entire area in which he is interested. If he has detailed information covering a part of his area, he can extrapolate, on the basis of the

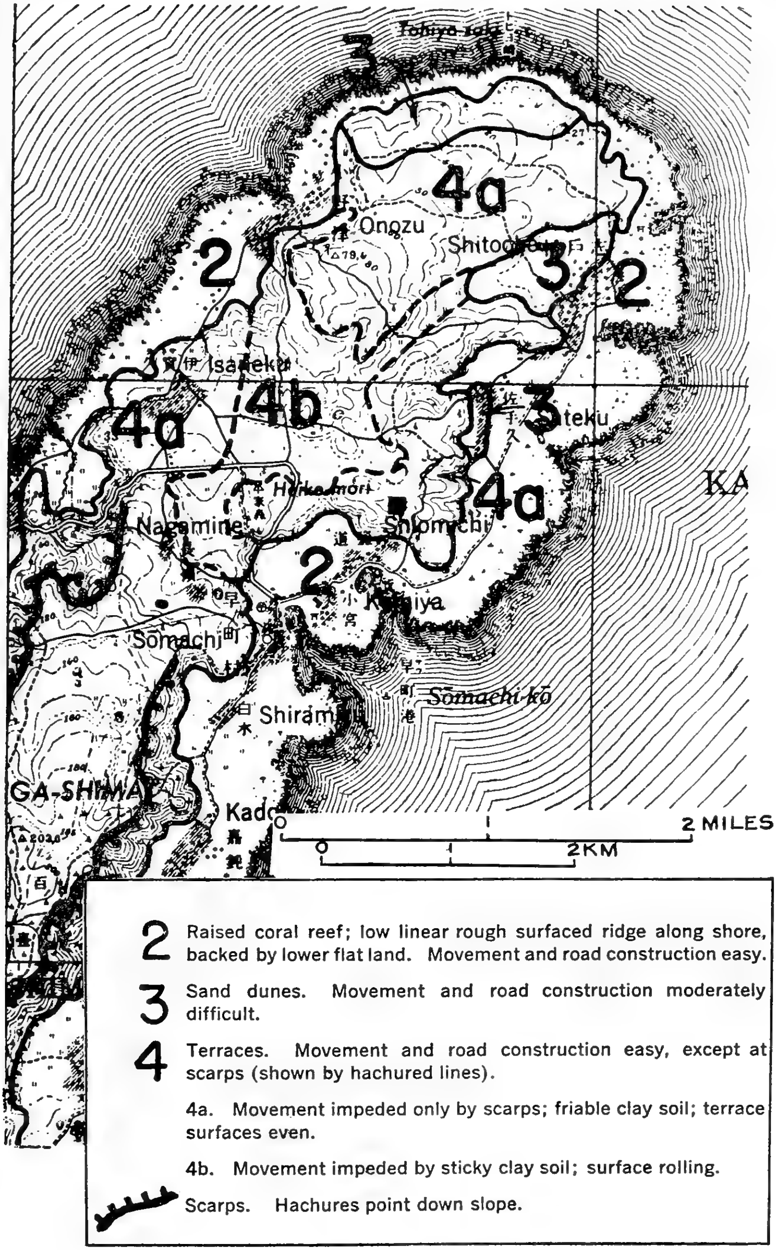

FIG. 1. Terrain map (sample from strategic engineering study prepared by Military Geology Unit, U. S. Geological Survey).

TABLE

THE MOST IMPORTANT ROCKS

[After von Bülow (1938);

Rocks	(a) Occurrence and Land Forms (b) Jointing	Condition of Weathered Rock Mantle in Horizontal Position [3]	Water Permeability [2]	Filtering ability [2]	Loosing Facility, Workability [1]	Stability [2]	Structural Roof Strength [2]
Sedimentary Rocks Sandstone	(a) Knobs, hills, plateaus (terrace topography) (b) Thick-bedded, platy, jointed	Sandy or loamy, depending on cement of sandstone	II–III	II–III	4–5	I–III(g)	I–III
Quartzite	(a) Steeper slopes, otherwise as above (b) Like sandstone	Stony, not very thick, only seldom actually loamy	IV–V	Mostly IV–V Percolation in joints	4–5	I–III	I–III
Graywacke	Like sandstone	Sandy, loamy, often quite thick	III–V	II–III; reason same as above	4–5	I–III(g)	I–III
Conglomerate, breccia	(a) Like quartzite (b) Thick-bedded to irregular, depending on geologic structure	Stony	Very variable, mostly III–I	Very variable, mostly IV–II	Very variable, II–V(h)	I–III	II–IV
Slate	(a) Hilly topography; upland surfaces with steep valleys (b) Cleavable in one or more directions	Loamy, partly sandy, mostly quite thick	IV–V	IV–III	3–5	I–IV(g)	II–IV
Marl, shale, shaly marl, indurated marl	(a) Like sandstone but more subdued; depressions in the mountains, etc. (b) Shaly or laminated	Loamy or marly-clayey, also of plastic consistency	IV–V	IV–III	3	IV–V(k)	IV–III
Limestone, dolomitic limestone, marble	(a) Knobs, hills, ridges, caves, sinkholes, plateaus (b) Thick-bedded, platy, jointed	Calcareous, loamy; often very thick and then poor in lime	II–IV	Owing to the numerous joints, mostly V–IV	4–5	I–III(l)	I–III
Gypsum-rock	(a) Usually barren hills (b) Jointed, honeycombed with cavities	Usually in very thin beds, calcareous, loamy	IV–II	V–IV	3–4	III–IV	III–V
Volcanic tuffs	(a) Very varied, massive or stratified, porous	Mostly loamy	II–IV	II–III	3–5	III–IV	III–IV

1

AND THEIR PROPERTIES

translated by Kurt Lowe]

Loading Capacity [2]	Suitability for: Construction site [2]	Compacted subgrade [2]	Pavement [2]	Road metal [3]	Crushed rock [2]	Concrete aggregate [2]	Fill [2]	Remarks
II–III	II	IV	II–IV	V	V	III–IV	If mixed with sufficiently fine-grained material: II–III	(g) Sometimes danger of sliding when dipping
I–II	I–II	II–III	I–III	II–III	I–III	I–II		
I–II	I	I	I–II	II–III	II–III	II–III		(g) Same as sandstone
II–III	I–II	II–V	Conglomerate III–IV; breccia mostly V	Conglomerate III–IV; Breccia II–III(h)	Conglomerate IV–V; Breccia I–III(h)	III–IV II–III(h)		(h) Loosely cemented breccia, easily loosed; after screening, suitable for road metal, crushed rock, concrete aggregate
II–III	II	III–IV(i)	V	V	V	V		(g) Sometimes danger of sliding when dipping (i) Fragments should be placed on edge
III	III	V	V	V	V	V		(k) Sometimes danger of sliding when dipping and after rainfall
II	I–II	III	V	II–V(m)	V	II–III, loamy dolomitic limestone		(l) When dipping, IV; sometimes danger of sliding (m) Dolomitic limestone not suitable for railroad construction
III–IV	III–V	V	V	V	V	V		
III–IV	III	V	V	V	V	V		

TABLE

Rocks	(a) Occurrence and Land Forms (b) Jointing	Condition of Weathered Rock Mantle in Horizontal Position [3]	Water Permeability [2]	Filtering ability [2]	Loosing Facility, Workability [1]	Stability [2]	Structural Roof Strength [2]
Sand	(a) River banks, plains, often in form of knobs rising from level topography	Loamy sand, sometimes hard residual soil	I–IV(n)	III–I(o)	1–2	III–IV	IV
Gravel, cobbles, and boulders	(a) Like sand	Stony soil	I	III–V	2–3	IV–V	IV
Compacted moraine material, erratics	(a) In level topography: terminal moraine ridges, terrain with small knobs	Stony loam or sand soil	I	IV–V	2	II–V	IV
Loam	(a) Plains, subdued hill topography, flood plains, lower slopes	Loam soil	III–IV, also V(s)	II–I	2	II–III; when wet: IV–V	IV
Boulder clay (u) (Boulder marl)	As above, but not on flood plains	As above, stony	III–V(t)	II	2–3	II–III; when wet: IV–V	IV
Loess-loam	Slopes, margins of flood plains	Thick loam soil, free from stones	II–IV	I–II	2	III; when wet: V	IV
Loess	Plains, plateaus, slopes	As above	I–II	I–II	2	III; when wet: V	IV
Marl	Like loam	Loam soil, partially containing lime	II–III(w)	II–III	2–3	II–V	IV
Calcareous and marly weathering crusts (caliche); bog lime and clay; oozes	Shore lines, swampy meadows	Calcareous humus	IV–V	V	2–3	III–V	V
Moor and peat	Lowlands	Wet, raw humus (peat)	III–V	I–II	1	V	V
Clay (u)	Like loam	Tough, impervious soil	V	I–II	2–3 [4]	IV–V	IV

The data above refer to fresh, unweathered rock.

[1] Classes of workability: 1, with shovel and spade; 2, pick and shovel; 3, mattock, crowbar, and iron wedge; 4, compressed-air drill and repeated blasting; 5, compressed-air drill and continuous blasting, together with crowbar, iron wedge, chisel, spade, and pick.

1 (*Continued*)

Loading Capacity[2]	Suitability for: Construction site[2]	Compacted subgrade[2]	Pavement[2]	Road metal[3]	Crushed rock[2]	Concrete aggregate[2]	Fill[2]	Remarks
II(*q*)	II(*q*)	.....	.....	.....	.....	I(*p*)	I–IV	(*q*) When lateral displacement is impossible (*n*) Rises with increasing grain size (*o*) Increases with decreasing grain size (*p*) If free from loam and clay (requires washing)
II(*q*)	II(*q*)	.....	.....	II–III	II–III	I(*r*)	I–IV	(*n*) Rises with increasing grain size (*r*) If free from loam and clay (washing) and if containing only few shaly fragments
II–IV	II–IV	II	av.: III	II–III	II–III	II–III	av.: III	
II–III	II–III	.....	.....	.....	.....	.....	III–IV(*t*)	(*s*) Rises with increasing sand content (*t*) Cavities form easily
II–IV(*t*)	II–IV(*t*)	.....	.....	.....	.....	.....	III–IV(*t*)	(*t*) Cavities form easily (*u*) Waterproofing material
III; when dipping: IV–V	III–IV	.....	.....	.....	.....	.....	III–V(*v*)	(*v*) Cannot be used for hydraulic construction
III; when dipping: IV–V	III–IV	.....	.....	.....	.....	.....	III–V(*v*)	(*v*) Cannot be used for hydraulic construction
II–III	II–III	.....	.....	.....	.....	.....	III–IV	(*w*) Decreases with rise in clay content
IV–V	IV–V	.....	.....	.....	.....	.....	V	
V	V	.....	.....	.....	....	.....	V	
III; when wet: IV–V	III; when wet: IV–V	.....	.....	.....	.....	.....	I–V(*x*)	(*x*) Can be used for clay cores (*u*) Waterproofing material

[2] Scale applicable to all other properties: I, excellent; II, good; III, adequate or fair; IV, poor, or usable only in emergency; V, inadequate, unsuitable, or absent.
[3] The rock mantle becomes thin along the slope and disappears altogether at scarps.
[4] When wet, best worked with hoe or drainage spade.

surface expression of known rocks, to a close approximation of the geology of the rest of the area. This was done during the war in the preparation of most of the Strategic Engineering Studies of the Military Geology Unit, U. S. Geological Survey, prepared for the Office of the Chief of Engineers. An example is the terrain-intelligence study of the Marianas Islands, prepared in 1944. No detailed information on geol-

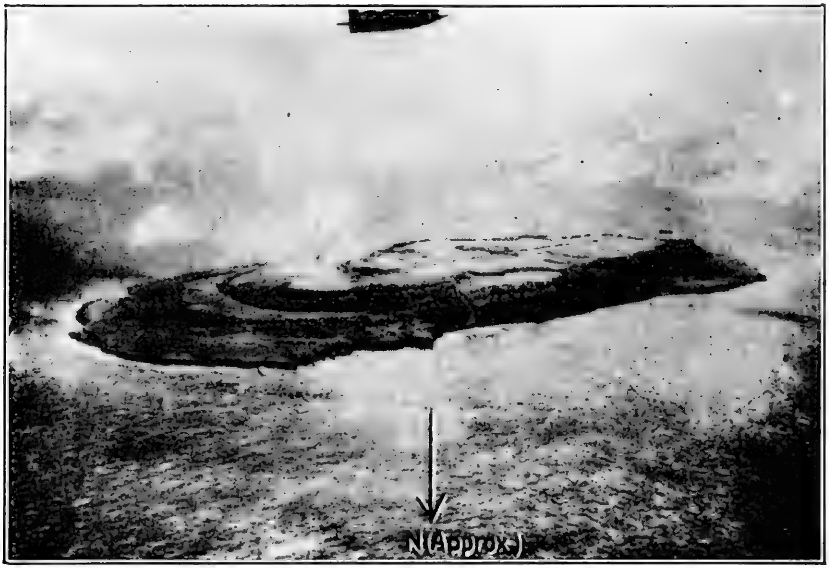

FIG. 2. Oblique aerial photograph of Aguijan Island, Marianas Group, looking south. (U. S. Navy photograph.)

ogy or soils was available, and the most complete Japanese articles were available only in abstract. There were no surveyed topographic maps. However, the geologists had access to low-level oblique aerial photographs, taken one month before the study was begun (Fig. 2). These showed the southern islands of the group (Guam, Saipan, Tinian, Aguijan, and Rota) to consist largely of raised coral-reef terraces. The higher terraces, generally above 600 feet, are much dissected; the lower terraces are broad and flat. Volcanic extrusives form rugged spines on some of the islands. Alluvium fills some small coastal embayments.

Brief published notes, plus knowledge of volcanoes to the north, led to the identification of limestones with interbedded tuff; elsewhere, uninterrupted limestone sequences were known to exist. This knowledge of the approximate distribution of the few rock types allowed prediction of the composition of the alluvium. The known mode of formation of reef rock made it a relatively simple matter to define it in terms of porosity, toughness, and mode of occurrence (large coral heads with matrix of fine-grained coral fragments).

In turn, the soil types of the Marianas were defined, on the basis of parent materials, vegetation, and relief, as follows:

(1) Stony clays, clay loams, and loams derived from limestone. Residual soil, containing friable clay (the result of laterization), with sand content dependent on amount of sand in parent material.

(2) Clay soils derived from volcanic rocks. Generally thin mantle of friable red clay.

(3) Coarse-textured alluvial soils of coastal plains (texture and composition varying with source material, distance transported, and relief).

(4) Fine-textured alluvial soils and swamp soils.

When the origin of these sediments is known, it is possible to predict their engineering properties with reasonable accuracy. For example, the residual friable lateritic clay of the Marianas, Ryukyus, and other tropical and subtropical islands is known to be fairly well-drained and to dry rapidly when not disturbed by vehicles or other heavy use; it is generally shallow, of irregular depth, with numerous rock outcrops.

Even more closely related to the study of sedimentation is the identification in aerial photographs of depositional features, such as dunes, bars, spits, beaches, glacial moraines of recent origin, stream-terrace deposits, active alluvial fans, and some volcanic deposits (Hack, 1948). These are especially recognizable in dry or cold climates where they are not obscured by vegetation, and their texture and composition are determined easily enough to be well-defined in simple terms. However, where vegetation mantles the earth, it can often be turned to the advantage of the terrain analyst as an indicator of the underlying materials. Vegetation is being used in this way in the study of permafrost (see Chapter 14 in this symposium), and it was utilized with great profit during the war to predict tropical ground conditions. For instance, the nipa and sago palm of the southwest Pacific indicate poor drainage conditions wherever found. Unfortunately, most plants are not restricted to a single type of substratum, or their ecology and relation to bedrock and soil are not yet sufficiently understood (U. S. War Department, 1944a).

TRAFFICABILITY

The possibility of cross-country vehicular movement depends primarily on the slope, porosity, and permeability of the ground, and on the cohesion of its constituent particles under repeated passes by traffic. But determination of these factors by no means solves the problem, because cross-country movement is also influenced by natural and artificial obstacles, snow cover, and the greatly varying ability of the military (or other) driver.

In preparing for a military operation, staff planners must be informed about where vehicles can move and where they cannot. If the expectable amount of precipitation in any season can be determined, and the physical properties of the soil have been deduced, a reasonable prediction can be made of the length of time necessary for the drying of various soils after rain or snow to the point where cross-country movement is again possible.

During the recent war, the Military Geology Unit of the U. S. Geological Survey prepared trafficability maps for use in France and Germany, using as sources a series of excellent published bedrock, soil, and glacial drift maps. The trafficability maps were based on the following legend:

1. Mountains and steep hills (most slopes 25 percent or more); steep, rocky, and terraced slopes. *Vehicular movement generally confined to roads;* tracked vehicles can operate on some mountain slopes.
2. (*a*) Hills with sandy or gravelly soils (slopes 7.5 to 25 percent). *Trafficable in all weather.*
   (*b*) Hills with loamy soils (slopes 7.5 to 25 percent. *Trafficability hampered by mud in wet weather, good in dry weather;* soils dry quickly.
   (*c*) Hills with clayey soils (slopes 7.5 to 25 percent). *Trafficability hampered by deep mud in wet weather; good in dry weather;* soils dry slowly.
3. (*a*) Gently sloping and level land; sandy or gravelly soils (slopes less than 7.5 percent). *Trafficability generally good to excellent in all weather.* Locally sand dunes hamper movement.
   (*b*) Gently sloping and level land; loamy soils (slopes less than 7.5 percent). *Trafficability hampered by mud in wet weather; good in dry weather;* soils dry quickly except where water table is high.
   (*c*) Gently sloping and level land; clayey soils (slopes less than 7.5 percent). *Trafficability hampered by deep mud in wet weather, good in dry weather;* soils dry slowly.
4. (*a*) Flat, low-lying, wet meadowland. *Trafficability very poor except when frozen or after prolonged dry spells;* soils sandy to peaty; water table generally near or at surface.
   (*b*) Swamps and peat bogs. *Cross-country vehicular movement difficult or impossible because of boggy soil conditions. Foot movement very difficult except when ground is frozen.*
5. Drained swamps. *Untrafficable because of closely spaced canals and ditches.* Destruction of drainage system causes flooding and boggy soils.

6. River flood plains; complex of well-drained and poorly drained soils. *Trafficability hampered by local areas of muddy soils.* Flood hazard, especially in winter and spring.

Predictions of this degree of detail have been proved accurate by field use, but a more quantitative expression of trafficability characteristics of soil is necessary; accordingly instruments are being devised whose measurements of bearing strength of various soil horizons can be correlated with trafficability properties.

In contrast to the detailed data given by bearing-strength tests and similar measurements is the highly important military requirement for prediction of trafficability on a regional basis. Soil maps, the primary basic data for such predictions, are based on a genetic classification and are designed primarily for use in connection with agricultural problems. This vast amount of detailed information can be applied to trafficability prediction, as well as to the use of soils in construction, by redefining agricultural soil map units (or groups) in terms of various laboratory tests. This is now being done in a study of Fort Benning, Georgia, which is to be published by the Office of the Chief of Engineers, U. S. Army. Samples were taken of each of the major agricultural soil types in the area. These were subjected to the following tests at the laboratory of the Waterways Experiment Station, U. S. Engineer Department, Vicksburg, Mississippi: mechanical analysis (percent sand, silt, clay); Atterberg limits; ratio, expressed as percent, of weight of contained water to weight of solid particles; and optimum dry weight (pounds per cubic foot). On the basis of these tests, each of the 64 soil series, types, and phases was assigned an airfield classification group symbol (U. S. War Department, 1944b). Each such group includes from two to ten agricultural soil units and is defined in terms of drainage, plasticity, dry strength, void ratio, compaction characteristics, optimum compaction (pounds per cubic foot), and California bearing ratio for compacted and soaked samples. Besides these general soil characteristics each group is defined in terms of its value for embankment, foundation, and base course, the effect on it of frost action, and its shrinkage, expansion, and elasticity.

Water Supply

Water for troop use is secured at the surface wherever possible, because of the greater speed and convenience involved. Ground water must be sought, of course, in arid regions; and even in humid climates it is often necessary to seek subsurface water because of contamination of the more obvious supply. Criteria and methods of the civilian water-supply geologist and hydraulic engineer are generally applicable except that, in supplying troops in the field, it is more expedient to develop easily reached supplies of small yield than to drill deeper for more adequate supply (U. S. War Department, 1945).

Construction Materials

Sand and gravel for concrete aggregate, fill, and base course are the earth materials most in demand for rapid military construction. Clay, for mixing with coarser material as binder, is needed. Crushed rock must be procured for road metal and ballast. To a lesser extent, rock must be quarried for riprap and for rough-cut dimension stone to be used in hasty fortifications or other structures.

The properties required for these uses are discussed in Chapters 8 and 24 of this symposium; the peculiarly military problems in regard to geologic construction materials are (1) locating them in advance of operations, generally by means of aerial photographs, and (2) utilizing substitute materials when circumstances prevent use of those normally specified for a given purpose.

In developing rock material for engineering use, either civil or military, the following major factors must be considered: accessibility, overburden, volume, and geologic structure. When considered in the light of purely military operations, however, the relative emphasis accorded these factors may vary greatly. The accessibility factor may be taken as an example. Normal military usage requires development of construction materials sources within 5 miles of the project site, but, when necessary, as in the Leyte operation, hauls may be resorted to that result in as much as a 5-hour round trip per truck per load; unheard of, of course, in civil-engineering practice.

Military structures built under operational conditions are not expected to last long. Materials requirements are not, therefore, so rigorous as in civil engineering. Within the resulting wider range of acceptability, choice of materials is likely to be governed mainly by the equipment available. Consider, as an example, development of concrete aggregate by a construction battalion operating in a large valley. If a dragline is available, stream gravels will probably be used; if bulldozers are at hand, a stripping operation may be begun on a gravel terrace.

In the search for sand and gravel, river banks, bars, terraces, and flood plains have long been the mainstay of the military engineer. The less obvious sources, such as abandoned stream channels, glacial-outwash deposits, and eskers, being recognizable in aerial photographs, were utilized in the last war. An example of this is the location of gravel during the Leyte campaign (Gilluly, unpublished manuscript). In this campaign, Gilluly reports the application of the following simple rules to the location of gravels: (*a*) decrease in grade size of gravel, from the upper reaches to the lower, of streams leaving the mountains for the plains; (*b*) lateral variation of grade size away from the river, with the coarsest gravel forming a low natural levee directly along the stream; (*c*) the tendency of streams to deposit on the inside of meanders, which led to location of at least three deposits in abandoned stream channels, each buried beneath 2 or 3 feet of soil.

Fortunately for the military engineer, his major construction projects are likely to be situated on lowlands, especially flood plains, where the chances of obtaining sufficient supplies of suitable sand and gravel are good. These source areas can be readily located by reconnaissance, especially if they have been delineated in advance on aerial photographs or on geologic maps.

An effective means of reconnaissance, although not particularly suitable for combat conditions, is the helicopter. One was used with signal success in locating gravel pits in Quaternary terraces on the Tokyo Plain, when the United States occupation forces were expanding Japanese airfields in 1946 (personal communication from Allen H. Nicol, Geologist, U. S. Geological Survey).

In addition to sand and gravel, crushed rock is a constant military need. It is used especially for base course and for road metal. The properties desirable in crushed rock are discussed in many texts (Legget, 1939; Ries and Watson, 1936); suffice it to say that resistance to wear is the most important.

As the best crushed rock is of igneous origin, a full discussion of the subject is not appropriate here. Well-cemented sandstones (especially those in which the grains are not in contact), quartzites, and some particularly resistant limestones make effective substitutes, and it has sometimes been necessary to crush large boulders from coarse gravels. The latter expedient is a particularly difficult one; because of the selective process of water transportation, the boulders are likely to be very hard and tough, and the relatively light crushers available to most Army Engineer units are almost unable to cope with them. The use of such materials was especially common in the tropics, where great depth of soil weathering made location of quarries difficult and, in places, seemingly impossible.

The examples cited here emphasize two of the major difficulties of the military engineer: the necessity for using substandard materials, and problems of construction in unfamiliar environments, especially the tropics, the sub-Arctic, and the Arctic.

Concerning the use of substitute materials, little more need be said. Once the necessity for such substitution is recognized, it is obvious that granite, despite its obvious shortcomings, can be used as road metal in place of basalt; that ordinary surface loam can be used as binder instead of clay or can be stabilized with some substance such as bitumen to serve, say, as an emergency airstrip surface. The geologic principles used in locating such substitute materials are the same as those applied in the search for the best possible ones.

It is the strange environment that now, as during the war, presents the greatest challenge to the geologist, engineer, and soil scientist who are trying to predict terrain conditions in foreign areas of operation. All three made predictions and calculations, based on training and experience in temperate zones, which did not apply elsewhere. It was at first taken for granted, for instance, that the moisture content of tropical clays could be reduced by working and reworking with earth-moving equipment. This proved to be far from true, because the clays in question were friable or "lateritic"; when worked carefully they are well-drained, but excessive working turns them to a morass. Another example, seen on Leyte, was the weathered condition of the interior of pebbles in the high terrace gravels that rendered them useless for construction (Putnam, unpublished manuscript).

Because of the depth of weathering in the tropics, interpretation of geology from aerial photographs is likely to be difficult on a physiographic basis alone, especially when such a control as knowledge of the stratigraphic column of part of the area is lacking. For this reason, vegetation has become important in the search for construction materials in the tropics (U. S. War Department, 1944a).

Coral is another tropical material in the use of which American engineers had little experience until World War II. Even now much remains to be learned about its properties as construction material, for coral differs widely in hardness, toughness, texture, and case-hardening properties. These affect not only its use as a building material, but also its properties as a subgrade or foundation.

Coral sand and gravel and crushed coral were used extensively during the war for the foundation of airfields and other structures. As base material and foundation rock, coral was poor to good in proportion to the clay content; a thick overburden of weathered coral also decreased its usefulness for these purposes. Massive coral requires blasting and crushing; therefore, because of the demand for speed in construction, the softer portions of the coral deposits were used, and thereby more or less clay and weathered coral were incorporated. On a clay base, the addition of fill carrying 50 percent or more clay with coral fragments was generally unsatisfactory.

Crushed hard coral proved satisfactory for base course, surfacing, and aggregates. It is easily stabilized with asphalt and bitumen. Large deposits of compact, fine-grained crystalline coral limestone are fully as satisfactory as ordinary limestone for use as riprap or masonry.

Coral sand, silt, and clay have a tendency toward self-cementing after placing and compaction. This has proved advantageous in airfield and road construction, as the coral rapidly cements itself to a fairly hard surface.

Massive coral has been effectively used as cyclopean riprap in breakwater construction on Guam (personal communication from Allen H. Nicol, U. S. Geological Survey). The "boulders" so used are about 10 feet in diameter.

In the future it is likely that further engineering uses for coral will be developed because of its diverse properties, especially when coral areas have been mapped in detail; for instance, there are commonly "pockets" of hard coral in raised reef strata which generally are soft. Many of these variations have not been fully explained in terms of chemical processes or of ecology. For example, an extremely hard, brecciated, but massive, coral stratum is found in Saipan.

As would be expected, coral is likely to be cavernous. Furthermore, its contact with the overlying residual clay, while extraordinarily sharp, is also extraordinarily irregular, with pinnacles several feet high extending into the overburden. Because of these characteristics, coral presents problems when used as a foundation. This is especially true when construction changes the established drainage pattern and cavern fill is washed away. Serious cave-ins may result.

Construction in the sub-Arctic and Arctic involves many as yet unsolved problems for the military engineer. As in the tropics, the strange environment necessitates an entirely new approach to many foundation- and construction-materials problems (see Chapter 14 in this symposium).

Airfield Siting and Construction

The military geologist is concerned with the siting of temporary airfields mainly. These range from hastily leveled emergency landing strips to extensive installations which, however, are rapidly built from local materials and have an expected useful life of perhaps 5 years.

The properties of sedimentary materials must be considered in the following aspects of airfield siting and construction: drainage and possibility of flooding; bearing strength; sources of gravel and crushed rock for base course, surface course, and concrete aggregate; and water supply for construction, maintenance, and human consumption.

In time of war, military airfield-site selection is unique primarily in that the geologist or engineer must select sites in areas he has never seen. With sufficient information, it is possible to select an actual runway location and describe subgrade conditions in considerable detail, or to determine the possibility of enlarging an existing field.

The methods of site selection differ, of course, with the amount of available information. The most difficult situation, where data were almost completely lacking, is exemplified by the selection of sites in the Solomon Islands by the Military Geology Unit in 1942. Geologic information was even more meager than topographic data; aerial photographic coverage was scanty or lacking. The only topographic information was on hydrographic charts on which the inland topography was indicated in a very general manner by hachures. With the help of scattered and general ground descriptions, and geologic interpretations based on analogous regions, areas were outlined within which the best sites were likely to be found.

On Guadalcanal Island the most suitable part for airfields seemed to be the coastal lowland along the north side (Fig. 3, areas 10 and 11). Several good anchorages were known along this coast, and these made it readily accessible. The eastern part of the lowland (area 11) was known to be thickly wooded, and large trees would present a clearing problem, whereas the western part (area 10) contained open patches of tall-grass prairie. By analogy with similar coastal plains, the lowland was expected to be an undulating plain within which expanses of level, fairly well-drained ground sufficiently large for airfields could be found. Some filling or diversion of small streams was anticipated for long runways. From its shape and position near the mouth of a large stream (Lunga River), Lunga Point at the west end of area 10 was described as a probable delta (hence poorly drained and less suitable for airfields than other parts). Because of the heavy rainfall, water supply would be adequate everywhere.

The Guadalcanal landing was made on the beach east of Lunga Point. Henderson Field was constructed on the site of a small Japanese airstrip on the grassy plain at the inland edge of the Lunga River delta. Another large airfield was built farther east within area 10.

When engineers are on the ground, ready to begin construction in a selected area, preconstruction reconnaissance is, of course, necessary in order to locate the airfield in the most advantageous position and to become aware in detail of the problems to be faced. The geologist, in his reconnaissance report, should include the following information:

(1) Description of the ground to a depth of 5 to 10 feet, behavior of subsoil water, and influence of atmospheric precipitation on the firmness of the ground surface.

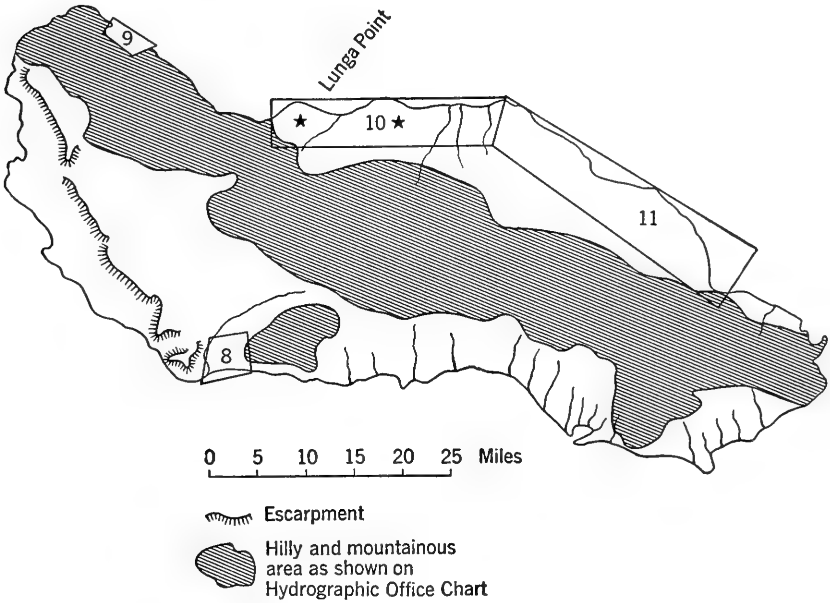

Fig. 3. Airfield-siting map of Guadalcanal Island prepared in July 1942, one month before the landing. Areas 10 and 11 were classed as the most suitable for airfields and areas 8 and 9 as less satisfactory. The stars indicate airfields constructed on the island after the landing. The airfield at the west is Henderson Field.

(2) Description of the general stability of the area: landslips, cave-ins, cavernous formations.

(3) Possible construction materials and recommendations for development of gravel pits or quarries.

Most airfields are built on flood plains; therefore not only drainage but flooding also must be carefully considered. Height and fluctuation of the water table must be determined in detail; the regimen of nearby streams must be known so that flood-prevention measures may be prepared.

As has been mentioned, many natural materials, including coral and "laterite," have been successfully used as airfield surfacing. In order that such materials may be used wherever available, the following laboratory determinations should be made for soil from the airfield site: granulometric composition, specific gravity, moisture content, filtration coefficient, plasticity (for clayey soils), and coefficient of internal friction (Bogomolov, 1945).

ROADS

The military geologist, like the military engineer, is more concerned with road maintenance than with construction. This is mainly a matter of locating ballast, fill, and surfacing materials; the geologic problems encountered are generally the same as those met in airfield construction.

UNDERGROUND INSTALLATIONS

Underground field fortifications have concerned geologists since World War I (Brooks, 1920). During World War II, as a protective measure against heavy bombing, the Germans went far in the construction of underground factories.

The term "hasty fortifications" will serve to include earthworks and excavated defense works constructed or dug in the combat zone, as opposed to permanent fortifications such as the Maginot Line. A hasty fortification may be a slit trench, or it may be a complicated and extensive system such as that dug by the Japanese in the loess and marl cliffs back of Kujukurihama, one of the beaches selected by the Allies for the landings leading to the attack on Tokyo. Such works are almost always constructed in unconsolidated sediments.

In such hasty construction, ground water presents a difficult problem. To insure dry excavations by proper location and by effective construction measures, it is of course highly desirable that the geologist have logs of local wells. If these are lacking, air or ground reconnaissance and intensive study of large-scale soil and geologic maps or aerial photographs will contribute much to the solution of the problem. Seasonal fluctuations of ground water must be considered, together with the water-bearing characteristics of various sediments. For instance, von Bülow (1938) states that seepage water is concentrated in the boundary zone between weathered and unweathered clay, usually at a depth of 1 to 2 meters.

Most extensive emergency military excavations are in lowlands; therefore they must go below the water table. They must be protected by impervious strata to a thickness of at least 6 feet, or else sealed off from ground water. Various means of effecting this are discussed and illustrated by Brooks (1920).

The stability of loose materials must also be considered (see Chapter 11 in this symposium). The ideal situation is the presence of nearly horizontal strata of constant thickness, although, in excavating into a back slope, a slight dip toward the tunnel entrance will facilitate haulage. In order to prevent cave-ins, thorough drainage must be insured and dipping strata carefully examined for intercalated clay layers and weathered zones that may serve as slip planes. The stability of unconsolidated or semi-consolidated materials generally decreases with advanced rounding of their constituent grains. Stability of such materials can be increased by injecting fluid quick-setting cement (sodium or potassium silicate). This, however, is not often possible under military operational conditions.

By contrast, the recently developed interest in permanent underground installations is expressed in terms of factory-sized caves or excavations. It is the consensus that natural caves are useless for this purpose because of the torrential floods that are likely to occur in them. The problem that faces the engineer and the geologist is, therefore, the planning of excavations on a very large scale; it must be approached with the point of view of the civil engineer rather than with the "expedient" approach demanded of those involved in military construction.

Other Applications

The usefulness of metallic-mine detectors is sharply limited by the presence of such minerals as magnetite in beach sands. Field tests proved this on the Sagami Bay beaches, selected for landings in the invasion plan for the Tokyo Plain. The presence of such sands can be predicted by identification of their source terrane.

A subject that demands further study is the effect of shell fire on rock, with especial regard to its splintering qualities. Defining this with any degree of accuracy is a complicated process; it depends on, among other factors, whether the rock is fractured, massive, or stratified, wet or dry, the degree of weathering, and the amount of vegetation overlying it. The caliber and type of projectile must, of course, be considered, with especial regard to its penetrating power.

SUMMARY

The geologist can contribute to military intelligence and operations by his ability to predict ground conditions and the location, type, and amount of ground water and of useful earth materials. Cross-country movement and construction of underground installations and airfields are among the most important of many military operations which require, for proper planning and prosecution, an application of the principles of sedimentation. Further work is needed in predicting ground conditions from aerial photographs, especially in the Arctic, sub-Arctic, and tropics; this in turn will require greater knowledge of plants as indicators of kind of ground, and of the origin, distribution, and characteristics of such materials as coral and permanently frozen ground. The effect of soil on cross-country vehicular movement must be more quantitatively expressed than it can be at present; this and other military problems involving soil can be solved much more easily when it is possible to interpret the many existing genetic soil maps in terms of the engineering properties of soil.

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Chapter 35

APPLICATIONS OF SEDIMENTATION TO NAVAL PROBLEMS

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Applications of the study of sediments to naval problems are much broader than might be inferred from a strict interpretation of the term *sedimentation,* which is usually taken to mean the processes by which sediments are formed. This discussion therefore includes applications in the more general fields of sedimentary petrology and submarine geology. Also, the Navy's interest in these fields is not limited to investigations immediately applicable to today's problems. Well aware of the need for increasing our fund of basic scientific knowledge, and of the fact that future applications are not always predictable, the Navy Department undertakes or sponsors a number of fundamental research projects in the earth sciences. A few examples of these are listed as indications of the Navy's breadth of interest.

The information on which this article is based is scattered through reports and documents not readily available to the general public. Much of this information has not yet been published. The accompanying bibliography is therefore incomplete, and it is not possible to mention all those who participated in the work described. I can only express my general indebtedness to all the geologists, oceanographers, and others who contributed, especially during World War II.

FIELDS OF APPLICATION

The principal fields in which information on sediments applies to naval problems are in the use of underwater sound, in mining operations, in the installation of underwater equipment, in shore installations and amphibious operations, and, to a limited extent, in the operation of naval vessels.

Underwater Sound

The extensive use of underwater sound (sonar) equipment in undersea warfare during World War II demonstrated conclusively the profound effect of the medium on the results obtained. In deep water, detection ranges with echo-ranging equipment depend on temperature gradients in the water and on the sea state, as well as on type of equipment, ability of personnel, and type and speed of ship. In shallow water, the character of the bottom has proved to be more important than other oceanographic factors. A hard, smooth bottom, such as smooth sand, reflects the sound beam forward with comparatively little distortion and backward scattering, whereas a hard, rough bottom, such as rock, scatters so much sound back to an echo-ranging ship that the target echo may be masked, even at relatively short ranges, by the din of reverberation. So little sound is reflected from a soft mud bottom, on the other hand, that sound conditions are very similar to those in deep water. In listening, transmission conditions tend to be best over a smooth sand bottom and are successively poorer for rock, sand and mud, and mud. As reverberation is not involved, listening ranges are therefore usually longest over a smooth sand bottom, fairly long over rock or a firm bottom of mud and sand, and poorest over mud. Echo ranges, because of reverberation, tend to be shortest over coral, rock, and boulder-strewn bottoms, intermediate over mixed mud and sand, about the same over soft mud as in deep water, and longest over smooth sand.

Another factor that influences the range of detection by sonar gear is the background noise heard in the receiver. The character of the bottom affects the distribution of certain biological noise makers, particularly "snapping" shrimp. Snapping shrimp furnish one of the best examples of "pure" science suddenly becoming of operational importance in naval warfare.

There are several species of small shrimp (not to be confused with the edible one), which make a loud click by suddenly snapping a pincer. These animals are widely distributed throughout the world in tropical and subtropical waters (up to about the 50° winter isotherm), in depths less than 30 fathoms (180 feet). They are chiefly confined to rocky and coral bottoms, or those covered with cobbles and boulders, where their colonies may be so abundant that the continuous noise produced, as heard in a hydrophone, sounds like frying fat, burning twigs, or the static from a radio receiver during a storm (Johnson *et al.*, 1947). Under such conditions they seriously interfere with the use of listening equipment. Fish, particularly certain members of the croaker and drum families, also produce noise which may be troublesome, especially when they congregate seasonally in large schools (Loye and Proudfoot, 1946; Johnson, 1948). A great many other biological noises, not all identified with the producing species, have been noted during operations and experiments—the sea is far from silent. Like snapping shrimp, the distribution of many of these organisms is in part dependent on the type of bottom.

Mining Operations

With floating mines, anchored to the bottom, some information about the character of the bottom and of currents in the vicinity is useful to determine whether the mine will remain where it is placed. With ground mines (those lying upon the bottom), the applications are much more direct. To be effective, a ground mine should remain on the surface of the bottom, not sink in, and remain where it is placed. Whether it will do so depends on the type and degree of compaction of the bottom material, the amount of scour by waves and currents, and the movement of sand or other sediment. Of secondary importance is the color of the bottom and transparency of the water, as mines may be spotted from planes if they contrast with their background. The fouling of mines has also proved to be a problem, and the type and abundance of fouling organisms is in part dependent on the character of the bottom.

Installation of Underwater Equipment

In installing underwater equipment for detection or other purposes, a prime consideration is the stability of the installation. Here, again, as with ground mines, the character of the bottom, together with current and wave conditions, is of major importance. The bottom must be firm enough to bear the weight of the equipment, and stable enough so that the equipment will not be overturned as a result of scour, or covered by shifting sand. With underwater sonar equipment, the acoustic properties of the bottom are also important, and with cable-connected equipment the character of the bottom along the route followed by the cable may be critical. Ideal conditions occur when the cable is covered by a thin layer of sediment. When the cable is exposed, particularly on a rough bottom, catenaries are likely to be formed, and movement of the cable in the earth's magnetic field sets up interfering electrical noise in the equipment. A rocky or coral bottom, particularly in shallow water, is especially bad because motion of the cable on the exposed rocks quickly wears it through and thus involves costly maintenance. The ideal type of bottom for an installation, therefore, is a smooth sand where there is little movement; for cables, a mud or sand bottom is preferable to other types.

Shore Problems

The stability of beaches and harbors, which affect shore installations such as piers, jetties, groins, and temporary and permanent docking facilities, have been treated in Chapter 15 of this symposium and will not be discussed here. Additional shore problems, however, occur in amphibious operations (Seiwell, 1946). These are of two types: the effects on landing craft, and the trafficability of the beach. The successful navigation of landing craft through the breaker zone to the beach is not an easy problem, and different techniques may be required under different conditions. Studies made during World War II showed that the factors involved are the angle of approach, size, breaking point, and type of waves, and the topography of the beach and immediate offshore area. Coordinated oceanographic and sediment studies are thus required to determine the relative importance of the factors involved and the manner in which conditions change with time. The factors that affect the trafficability of a beach are less well-known. The size and shape, and the size and shape distribution of the particles, which affect permeability, porosity, compaction, and bedding, are known to be important, as are the variations in tide and wave levels and the slope of the beach, which affect drainage and air entrapment (Emery, 1945). Possibly the angle of wave approach and the types of waves may also be a factor.

Operation of Naval Vessels

Two applications of submarine geology and sedimentation to the operation of naval vessels are evident. First, detailed topographic maps of the bottom, in areas of some topographic relief, can be used for navigation (Shepard, 1948). The bottom profile along the course traversed by the ship may be matched to the map and the corrected course and location thus obtained. Second, submarines frequently find it necessary to lie on the bottom, either to effect repairs or to avoid detection. At such times the firmness and topography of the bottom are obviously of importance. In warfare, the camouflage characteristics of the bottom may also be important, as a submarine in enemy waters must avoid detection from the air. It may also make use of the acoustic properties of the bottom to evade detection or hinder tracking. A rocky bottom in shallow water will not only hamper the enemy in an echo-ranging search because of the high reverberation, but also may provide colonies of snapping shrimp which will considerably reduce the range of listening gear. World War II patrol reports indicate that our submarines made considerable use of information about the character of the bottom in evading Japanese antisubmarine vessels.

METHODS AND RESULTS

The methods of attack on most of the problems listed above are fairly obvious. They are: first, a determination of the factors involved and their relative importance by means of laboratory and field experiments; second, accumulation of data on the distribution of the important factors by means of surveys or by compilation of existing data; and, third, presentation of the information in suitable form for operational use by means of charts and manuals. Under wartime pressure, much of the first stage sometimes had to be omitted and educated guesses made on the pertinent factors and their relative importance. Thus, stages two and three were often entered without adequate background, and it has been necessary to go back to research and experiment to obtain additional information. Such data as have been accumulated during the past few years, however, have shown that most of the guesses were surprisingly good in view of the scanty data on which they were based.

Experimental Studies

Operational tests of sonar gear in shallow water, early in World War II, demonstrated the important effect of the bottom on the transmission and scattering of underwater sound. Geologic inference regarding the probable effects of various types of bottom was sufficiently confirmed by preliminary tests to justify the compilation and presentation of information for operational use. Subsequently, detailed field experiments were undertaken at the University of California Division of War Research (UCDWR), the Woods Hole Oceanographic Institution, and the Navy Underwater Sound Laboratory at New London. At San Diego particularly, where a variety of bottom types is available within easy operating range, detailed surveys were made and charts prepared of the distribution of bottom types, and sound transmission and reverberation measurements were made over these areas. The results (Eckart, n.d.; Bergmann, n.d.; Spitzer, n.d.) have led to the determination of reflection and scattering coefficients for certain types of bottom, but much yet remains to be learned, and the work is continuing at the Navy Electronics Laboratory and the Marine Physical Laboratory (University of California). Preliminary attempts were also made to measure the sound-transmitting and -absorbing qualities of various types of sediments in the laboratory, but these initial tests were generally unsatisfactory, and this portion of the field is still largely unexplored.

Some flume and model experiments, together with field measurements, have been made to determine the relative importance of factors that affect the stability of ground mines and of bottom-mounted equipment, but this field also lacks detailed quantitative data. More was accomplished during the war on the effects of waves, currents, submarine topography, and beach characteristics on landing operations, and work is continuing in connection with general studies of wave and beach phenomena. Much remains to be done, especially on the factors affecting the trafficability of beaches.

Surveys

Detailed surveys of the ocean floor, in which improved sampling devices and photographs of the bottom were used, have been made in connection with acoustic research and the installation of special electronic equipment on the bottom. The results of some of this work have been published (Emery, 1948a; Shepard, 1948), and more is in process of publication. Reconnaissance surveys, and data obtained by laboratory ships and by naval vessels on training operations such as "Highjump" (the Navy expedition to the Antarctic in 1946–47), are vastly increasing our knowledge of the sediments and topography of the ocean basins (Hess, 1948; Dietz, in press). It is estimated that several hundred cores and bottom photographs and several thousand surficial samples were taken by Navy activities and private research institutions with Navy contracts during 1949.

Charts and Manuals

One of the projects that engaged a number of geologists during World War II, including the writer and the editor of this symposium, was the compilation of all existing oceanographic information in areas of strategic importance, and the preparation of charts, texts, and manuals to enable naval operating forces to use this information effectively. Forty-three "Bottom Sediment Charts" were prepared by the UCDWR for areas along the Asiatic coast and Dutch East Indies; twenty-five of these were published by the Hydrographic Office (Shepard, Emery, and Gould, 1949). Others, made at Woods Hole Oceanographic Institution, covered parts of the Atlantic coast of the United States and small parts of the west coasts of Europe and Africa. "Submarine Supplements to the Sailing Directions," essentially climatic atlases of oceanographic conditions for submarines operating in enemy waters, also contained information on bottom types in shallow water and proved to be extremely valuable to our submarine forces. Numerous other charts and manuals, with information on beaches, bottom sediments, and similar geologic and oceanographic data, were prepared for special purposes.

Equipment

Several types of new equipment for determining the character of the ocean bottom have been developed as a by-product of the work described above. These include new types of grab samplers and corers (Ewing, Woollard, Vine, and Worzel, 1946; LaFond and Dietz, 1948), one of them for use from a ship underway (Emery and Champion, 1948), equipment for photographing the bottom (Ewing, Vine, and Worzel, 1946; Shepard and Emery, 1946), and new types of acoustic equipment. A hydrophone, adapted for dragging over the bottom, gives information on bottom character from the sounds produced (LaFond, Dietz, and Knauss, in press). Fathometers have been greatly improved. A new type, the "bottom scanner," presents a profile of the bottom below the ship on the face of a cathode-ray oscilloscope (Russell, 1946).

OTHER RESEARCH

In addition to the problems listed above, the Navy has undertaken or sponsored much research in sedimentation and submarine geology not immediately applicable to naval problems. Probably the outstanding example is the work done at Bikini and other atolls of the Marshalls in connection with the atomic bomb tests (Dobrin *et al.*, 1949; Emery, 1948b; Emery, Tracey, and Ladd, 1949; Ladd *et al.*, 1948; Munk and Sargent, 1948; Revelle, 1947; Sargent and Austin, 1949; Tracey *et al.*, 1948). When all the work accomplished during the summers of 1947 and 1948 is published, we shall have our first detailed account of the characteristics of a coral atoll.

Other examples of Navy or Navy-sponsored research are the joint sedimentation survey of Lake Mead, Nevada (cooperating agencies include the Bureau of Reclamation, the Geological Survey, the Coast and Geodetic Survey, and, for the Navy Department, the Bureau of Ships, the Bureau of Ordnance, the Hydrographic Office, and the Navy Electronics Laboratory); Ewing's geophysical work (Ewing, Woollard, and Vine, 1946; Ewing, Worzel, and Pekeris, 1948; Press and Ewing, 1948); Phleger's laboratory for the study of Recent foraminifera; and fundamental studies on waves and shore processes (Einstein, 1948; Inman, 1949; Munk and Traylor, 1947; Munk, 1948, 1949; Munk, Iglesias, and Folsom, 1948; Shepard and Inman, in press; Sverdrup and Munk, 1946a, b). Research on the Sofar (for *S*ound *F*ixing *A*nd *R*anging) network, recently established in the northeast Pacific by the Navy Electronics Laboratory for air-sea rescue purposes, should yield additional data of geologic importance (Ewing, Woollard, Vine, and Worzel, 1946; Ewing, Worzel, and Pekeris, 1948; Russell, in press).

Navy research thus offers many opportunities for those interested in marine sediments and submarine geology. Naval vessels provide means for taking data in all parts of the oceans. These data, with the research underway at Navy Laboratories and in private institutions on Navy contracts, are rapidly expanding our knowledge of the oceans, their processes, and their sedimentary products. This expansion may be expected to continue so long as funds are made available for research.

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