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THE PRINCIPLES
OF
ECONOMIC GEOLOGY

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BY

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PREFACE

This volume is an attempt to present as briefly as practicable a perspective of the science of metalliferous and nonmetalliferous deposits to advanced students of geology. It includes a series of lectures on economic geology which for the past ten years I have offered at the University of Chicago and at the University of Minnesota. These have been expanded and descriptions of certain mining districts have been added.

This work does not include a treatment of mineral fuels, an omission which perhaps is justified by the development of the geologic branches in our colleges. Coal deposits are treated at some length in text-books of general geology. Petroleum geology is treated in several texts on oil which are no more comprehensive than is desirable in a thorough course in economic geology. An equally comprehensive treatment would make this book so voluminous as to defeat some of its purposes.

The order of treatment is indicated in the table of contents. The first part of the book is a general treatment of mineral deposits. The second part is a treatment of each of the metals and of the more valuable nonmetallic minerals. Numerous mining districts and their deposits are described. There is no attempt to include discussions of all or even all the more valuable deposits of every metal. Examples are chosen to illustrate classes and as far as practicable they are chosen from North America.

The descriptions of mining districts are arranged so that some of them may be omitted in class-room work when that seems desirable. I am convinced that a few districts studied thoroughly are more helpful for instruction than many districts discussed in brief. In advanced classes, as a rule, many or all of the students are familiar with one or more districts as a result of field work. It is advantageous in lecturing to use such districts, as far as practicable, for purposes of illustration even if that results in giving inadequate treatment to more important districts. It is difficult in one or two lectures to give a student a clear picture of a district which he will retain and when fifty or a hundred districts have been described the difficulties are increased. Maps, photographs, and sets of rocks and ores from the larger districts are helpful, especially if these are before the student during the discussion. Even with such assistance probably better results may be obtained by omitting discussions of some districts treated herein.

Some readers doubtless will disagree with certain features of the classification of ore deposits (Fig. 6), also with the weights I have set down for certain processes in the formation of various ores and illustrated in Figs. 40 and 74. These weights will be changed as our knowledge of ore deposits increases. I have introduced these figures because I believe that they will help to give the student a perspective.

I acknowledge my indebtedness to Professors F. F. Grout, T. T. Quirke, and T. M. Broderick of the Department of Geology and Mineralogy of the University of Minnesota, who have critically read certain sections of this volume, and to Dr. E. C. Harder of the United States Geological Survey, who has read several sections, among them the chapters treating deposits of iron and manganese. Many of the drawings have been made by Mr. A. I. Levorsen and Mr. G. S. Nishihara. I have endeavored suitably to acknowledge sources of information by footnote references.

W. H. E.

University of Minnesota, Minneapolis,
December, 1917.

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THE PRINCIPLES OF ECONOMIC GEOLOGY

CHAPTER I

INTRODUCTION

An ore deposit is a geologic body that may be worked commercially for one or more metals. Ore deposits do not differ essentially in genesis from other geologic bodies. Many of them are simply igneous, sedimentary, or metamorphic rocks that contain materials which are valuable in the arts. Such rocks are treated in studies of general geology and petrology, which the student of economic geology is supposed to have mastered, and they are discussed but briefly here.

In general the geologist who is consulted on problems connected with ore deposits is expected to answer the questions, Where is the ore? How shall one find the deposit that is lost? What changes are likely to take place in depth? To what depth will the deposit continue to be profitable? These questions can be answered most intelligently by one who has an adequate knowledge of the structural and historical geology of the region containing the deposits, such as is gained by detailed mapping, together with an understanding of the genesis of the deposits, their relation to the structure, their deformation, and their superficial alteration and enrichment.

Deposits that have been precipitated from aqueous solutions in and along fractures in rocks receive but scant attention in the other branches of geologic science as now developed, and the study of such deposits is especially appropriate in the economic branch. Certain definitions, most of which refer to veins or to vein formation, are given below. The list is not exhaustive; the student is advised to refer to the index for other definitions that are introduced at appropriate places in the text.

An *ore* is a mineral or association of minerals that may, under favorable conditions, be worked commercially for the extraction of one or more metals.

Protore is low-grade metalliferous material which is not itself valuable but from which valuable ore may be formed by superficial alteration and enrichment.

An *ore mineral* is one that contains a valuable metal.

A *gangue mineral* is an earthy or nonmetallic mineral associated with the ore minerals of a deposit.

A *tabular body* is shaped like a tablet, short in one and long in two dimensions.

A *vein* is a mineral mass, more or less tabular, deposited by solutions in or along a fracture or group of fractures.

Country rock is the rock that incloses a metalliferous deposit.

Vein walls are the rock surfaces on the borders of veins. If there is much replacement of the country rock along the fissure the ore may grade into the wall rock and its walls may be indistinct.

A *druse* or *vug* is an unfilled portion of a vein.

Banded ore is ore composed of bands or layers (see Fig. 1). The layers may be composed of the same minerals differing in color or texture or proportions, or they may be composed of different minerals.

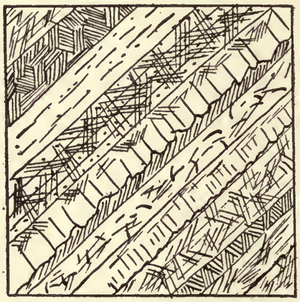

Fig. 1.—Section of banded vein.

Fig. 2.—Section of vein with crustified banding.

Crustification or crustified banding (Fig. 2) is produced when mineral layers of different character are deposited successively one upon another on the borders of openings. In *comb structure* elongated prisms project approximately at right angles to a surface, like teeth of a comb.

Symmetrical banding results where solutions deposit similar material on both sides of an opening, layer on layer, as shown in Fig. 3.

Vein material is the matter that constitutes veins, whether ore or gangue, workable or not workable.

Gouge is soft clay-like material that occurs at some places as a selvage between a vein and country rock. It is usually formed by the crushing of ore or country rock, or both.

Replacement is a process in the operation of which rocks and ores are slowly dissolved and material of different composition is deposited in the spaces which they occupied. Deposition follows solution closely so that forms and textures of earlier substances are often preserved. (See Figs. 4 and 5.)

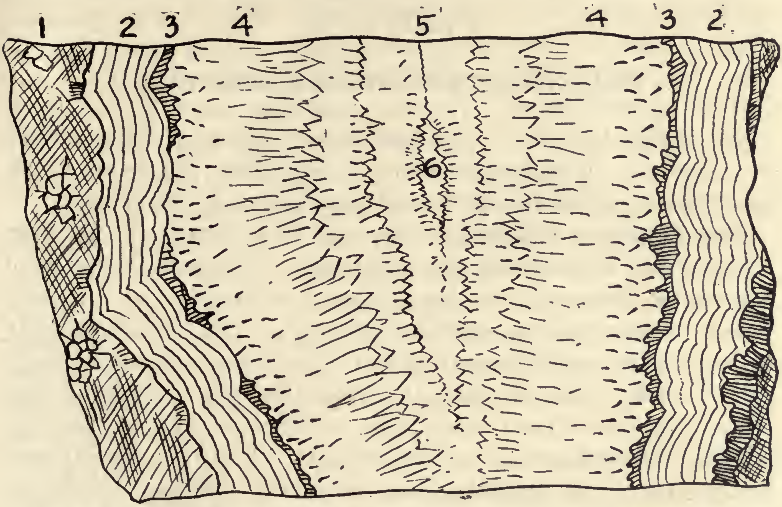

Fig. 3.—Section of vein with symmetrical crystified banding, natural size (Creede, Colo.). 1, Chlorite, quartz, sphalerite and galena; 2, finely banded quartz; 3, sphalerite and a little quartz; 4, amethystine quartz; 5, union of quartz combs; 6, vug.

Fig. 4.—Vein filling a fissure.

Fig. 5.—Replacement vein filling a fissure and replacing wall rock along the fissure.

The *paragenesis* of an ore expresses the relations of its minerals, especially the relations that bear upon its origin.

Hydrothermal alteration is a process by which rocks and ores are changed by hot waters.

CHAPTER II

CLASSIFICATION OF ORE DEPOSITS

A classification of ore deposits should recognize three groups of processes—those concerned in (1) deposition, (2) deformation, and (3) superficial alteration and enrichment of the deposits.

Ores deposited by any process may be deformed by faulting, folding, and deep-seated metamorphism. Through processes of superficial alteration ore deposits may be enriched or impoverished. Deposits that exist essentially as they were originally formed are termed *primary* deposits; those that have been altered by dynamic processes may be termed *deformed* deposits; and those that have been altered by superficial agencies are frequently referred to as *secondary* deposits. Part of a deposit may be primary and another part secondary. When metals are transferred either in solution or mechanically and deposited where there was no ore or protore before, the deposit is primary, whether it is a placer, a chemical sediment, or a vein.

CLASSIFICATION OF PRIMARY DEPOSITS

1. Deposits formed by magmatic segregation; consolidated from molten magmas.
2. Pegmatite veins; deposited by "aqueo-igneous" magmatic solutions.
3. Contact-metamorphic deposits; deposited in intruded rocks by fluids passing from consolidating intruding rocks.
4. Deposits of the deep vein zone; formed at high temperature and under great pressure, generally in and along fissures.
5. Deposits formed at moderate depths by ascending hot solutions.
6. Deposits formed at shallow depths by ascending hot solutions.
7. Deposits formed at moderate and shallow depths by cold meteoric solutions.
8. Sedimentary deposits; chemical, mechanical, organic, etc.

Syngenetic deposits are those formed contemporaneously with the inclosing rocks. They include deposits formed by magmatic segregation and sedimentary deposits.

Epigenetic deposits are formed later than the rocks that inclose them. They are deposited in openings in rocks, or by replacement.

Deposits formed by magmatic segregation are products of the differentiation of igneous magmas. Genetically considered they are in the strict sense igneous rocks. These deposits include ore bodies of considerable value, among them the great magnetite deposits of the Kiruna region, Sweden, and some of the magnetic iron ores of the Adirondack Mountains, in New York. No large sulphide deposits of this class are known in the United States. The nickel-copper deposits of Sudbury, Ontario, are the best-known examples of this group in North America.

In many places where igneous rocks rich in iron, nickel, or chromium minerals are weathered at the surface, especially under temperate or tropical conditions, the metals are concentrated, owing to the removal of other material. So prominent are the secondary processes in the genesis of such ores that they are classed by some as a distinct group, although the protores, or unworkable material from which the ores are derived by weathering, are igneous rocks.

Pegmatite veins are nearly related to deposits formed by magmatic segregation. They are end products of crystallization that have been thrust, like igneous dikes, into openings in rocks already consolidated. Pegmatites that have not moved from their parent magma and are not related to openings in rocks could properly be classed with syngenetic deposits, as deposits formed by magmatic segregation, but some authorities reserve the latter term for the more basic differentiation products. Pegmatites, although they supply many valuable non-metallic substances and many gems, are comparatively unimportant as sources of metals.

Contact-metamorphic deposits are formed in intruded rocks by fluids (liquids and gases) given off by intruding igneous magmas near by. They may generally be distinguished from lode deposits by their irregular shape and by their apparent independence of fissuring, together with the fairly constant association of the minerals they contain.

The deposits of the deep vein zone are mineralogically related more or less closely to contact-metamorphic deposits. They have formed in and along openings in rocks, however, and in the main they are more nearly tabular in form than the contact-metamorphic deposits. As pointed out by Lindgren, who first defined the group, the deposits of the deep zone have formed under conditions of high temperature and pressure, which prevail also in contact metamorphism. Because high temperature and pressure are necessary for their genesis, these deposits do not form at moderate and shallow depths, at least not in open fissures that extend to the surface, and for that reason they are seldom found in the more recent rocks. The deposits of the deep vein zone are affiliated on one hand with contact-metamorphic deposits and on the other with veins formed at moderate depths, from which they can not be sharply separated.

The deposits formed at moderate depths by ascending hot solutions constitute an important group. They differ from ores formed in the deep veins and from those formed at shallow depths in their mineral composition and in the character of the alteration of the wall rock accompanying their formation.

Deposits formed at shallow depths by ascending hot solutions are generally related to well-defined openings in rocks, such as fissures or to the intergranular spaces in conglomerates or sandstones or openings in vesicular lavas. These deposits may be distinguished from veins formed at moderate or greater depths by the minerals they contain and by the character of the alteration of their wall rocks.

The deposits formed at moderate and shallow depths by cold solutions include a large number of valuable deposits of lead and zinc in the Mississippi Valley and many small copper deposits in the Southwest. Much evidence has been cited to show that these deposits were formed by ground water that gathered its metallic contents from great masses of rocks in which the metals were sparingly disseminated. The metallic salts, chiefly sulphates, chlorides, and carbonates, were gathered in water channels, and the metals were deposited as sulphides where conditions were favorable. In many localities some form of organic material supplied the precipitating agent. If deposition had taken place on an older sulphide these deposits would be classed as secondary sulphide ores, but in general there is no evidence that bodies of older sulphide ore occupied the places of the deposits. These ores are therefore considered primary, although they have been leached by ground water from older metalliferous rocks.

Sedimentary beds of mechanical, organic, or chemical origin are the sources of many economic products, such as coal, clay, gypsum, salt, potash, lime, phosphate rock, iron, manganese, and placer gold. Workable sulphide deposits of sedimentary origin are exceedingly rare. Sedimentary deposits, like sedimentary rocks, are derived mainly from the decay of older rocks and older deposits.

Certain classes of ore deposits that have been recognized by some investigators seem not to be included in the foregoing classification. Among these are the "segregated veins" and "overlapping lenses" that are generally assumed to have been concentrated during dynamic or regional metamorphism, from substances contained in the country rock. Some of the ore bodies assumed to have been formed in such a manner are the dynamically metamorphosed deposits of the primary classes mentioned above. If such deposits are formed during dynamic metamorphism they should be placed with the deposits of the deep vein zone. They are uniformly associated with rocks that have been deformed beneath the surface by great pressures under heavy load.

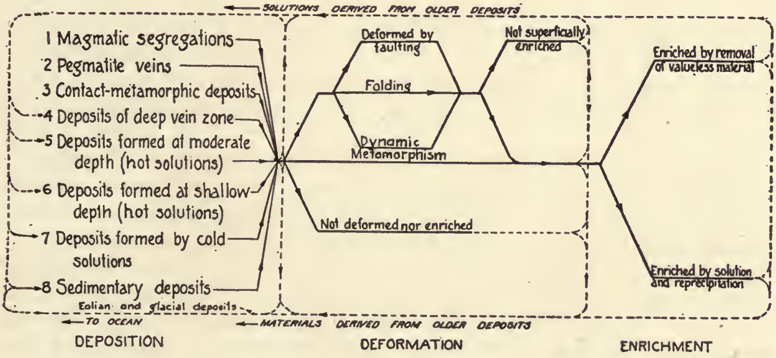

Fig. 6.—Diagram illustrating mode of deposition, deformation, superficial alteration and enrichment of ore deposits and protores. Diagram shows also how deposits may be broken down mechanically or dissolved and their products may enter new deposits. It is helpful to trace out on the diagram the genesis of several typical deposits.

Placers are deposits formed by mechanical processes from materials that resist weathering—such as gold, platinum, tin, and iron oxides. They are classed as sedimentary deposits, for they are formed in running or standing water.

"Land sediments," such as those formed in basins and in troughs that are dry part of the time and those formed on the slopes of hills, are likewise considered sedimentary, although less water has taken part in their transportation. A few of them contain gold placers. Deposits at the orifices of hot springs may also properly be classed with sedimentary beds.[1] Residual deposits may be classed according to the origin of the protore or material from which they were derived.

A diagram illustrating the classification of ore deposits is shown by Fig. 6.

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[1] In the outline above "aggradational deposits" could be substituted for "sedimentary deposits" and the group subdivided into sedimentary, glacial, and eolian deposits. This would give too much emphasis to glacial and eolian deposits, whose importance as sources of the metals is comparatively small. These deposits, however, yield nonmetallic products of value, including clays and sands. A place is provided for them in Fig. 6.

CHAPTER III

DEPOSITS FORMED BY MAGMATIC SEGREGATION

Occurrence.—In igneous rocks, principally in rocks that have crystallized slowly. Some but not all are at the bases or edges of rock units. Some dikes and stocks are all ore or protore.

Composition.—The minerals are the minerals of igneous rocks. The gangue minerals include quartz, feldspars, pyroxene, olivine, mica, and other rock-making minerals. In general the minerals of the parent country rock and the minerals of the deposit are similar, but the proportions are different. Metals won include iron, nickel, titanium, chromium, platinum, and subordinate copper and gold.

Shape.—Some are irregular in outline, others are rudely ellipsoidal, and still others are tabular.

Size.—Some are small and others are very large. The value of the ore per ton is generally low, and as a rule the deposit must be large to be of commercial value.

Texture.—The minerals are intergrown like the minerals of igneous rocks. Banding, though not uncommon, is not crustified as in veins. Miarolitic cavities are sometimes found in deposits formed by magmatic segregation, but these are not nearly so common as the vugs in veins, and they are not symmetrically lined, as is common in the unfilled portions of veins. The ore is contemporaneous with the parent country rock and grades into it, although in some deposits the gradational zones are narrow. Contacts with rocks that are not contemporaneous are not gradational. The rocks are not hydrothermally altered at the time of deposition of the ore. Idiomorphic rock-making crystals may be inclosed in the ore minerals. Fragments of intruded rock may be included in the ore.

General Features.—Some investigators use the term "magmatic segregation" for all ore deposits formed by waters of magmatic origin. As used here this term is applied only to those deposits which solidify from magmas. The deposits are therefore igneous rocks in a strict sense, but on account of their unusual character many of them are not always so regarded. Magmatic differentiation is the process by which a magma or molten rock stuff of supposed uniform composition splits up into bodies of different composition.[1] The subject properly belongs to petrology, but certain aspects should be considered here.

[1] Vogt, J. H. L.: Bildung von Erzlagerstätten durch Differentiationsprocesse in basischen Eruptivemagmata. *Zeitschr. prakt. Geologie*, vol. 1, pp. 4–11, 125–143, 257–284, 1893.

Under some conditions in a magma the heavy material settles to the bottom and the lighter material rises to the top, perhaps after the manner of separation of metals from slag in a blast furnace. Segregation may thus take place before crystallization begins.[1] Magmas are solutions and obey the laws of solutions. Thus the minerals that solidify or separate out from a cooling magma do so in the order of their saturation points under the conditions that prevail. As a general rule the more basic materials, such as iron, magnesium, and titanium minerals, will crystallize first. These in the main are the oxides and sulphides. As crystallization goes on the liquid portion generally becomes more and more acidic or siliceous, although some silica also may crystallize out early in the process. If viscosity is not too high, the heavy minerals fall. Later, if pressure is relieved by extravasation of the upper lighter molten liquid, the heavier material remaining at the bottom, owing to relief of pressure, may be remelted.[2]

Soret, in 1879, established the principle that when two parts of the same solution are at different temperatures there may be a concentration of the dissolved substance in the cooler portion of the solution. Differences in pressure also may cause differences in concentration.[3]

Becker[4] attacked the application of Soret's principle to magmas, urging that magmas are so viscous that diffusion would be too slow to permit the segregation of heterogeneous masses of large size. Becker[5] has shown also that fractional crystallization on cooling, in a dike or laccolith, may cause differentiation. Along the cooler walls the less soluble material will crystallize first, and convection currents will tend to carry the more soluble material into the still liquid portion of the mass, where it will later solidify. Thus the less soluble material will predominate

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[1] Morozewicz, J.: *Min. pet. Mitt.*, vol. 18, p. 233, 1898.

Daly, R. A.: Differentiation of a Secondary Magma through Gravitation Adjustment. *Rosenbusch Festschr.*, pp. 203–233, 1906.

[2] Schweig, Martin: Differentiation der Magma. *Neues Jahrb.*, Beilage Band 17, p. 516, 1903.

[3] Iddings, J. P.: The Origin of Igneous Rocks. Philos. Soc. Washington *Bull.* 12, pp. 89–130, 1892.

Iddings, J. P.: Igneous Rocks, pp. 1–464, 1909.

Pirsson, L. V.: Rocks and Rock Minerals, 414 pp., 1909.

[4] Becker, G. F.: Some Queries on Rock Differentiation. *Am. Jour. Sci.*, 4th ser., vol. 3, pp. 121, 257, 1897.

[5] *Idem*, p. 257.

on the outer walls. This process may be compared to the Pattinson process for desilverizing lead-silver ore. The argentiferous lead is melted, and as lead is precipitated at a lower temperature than a mixture of lead and silver, the lead will solidify first. It is ladled out from the rich lead-silver solution while the latter is still liquid. By this process a considerable concentration of silver results.

Although the mechanism of magmatic differentiation is not fully understood, there is much evidence that it has operated, for commonly an igneous rock grades almost imperceptibly into another igneous rock of different composition, although the two have formed from the same molten body. In comparatively rare examples one rock is peripheral with respect to the differentiated body.[1]

In many large bodies of igneous rocks, however, if not in most of them, the chemical composition is nearly uniform over large areas. It would be natural to suppose that the processes above outlined would operate to segregate the elements much more generally than they do. These processes are opposed by convection currents and other movements of the magmas, which tend to keep the solutions uniform, and by viscosity, which tends to prevent diffusion or movement of molecules through the mass. Whatever the cause, it is generally found that magmatic differentiation, if operative, is incomplete, and that more commonly than otherwise noteworthy proportions of magnetite, pyrite, or other heavy materials remain distributed throughout the great rock masses.

One other aspect of the subject of ores associated with igneous rocks should be mentioned. Practically all investigators agree that the magmas, or the igneous rocks, are the sources of all the metals. The study of the genesis of ore deposits is therefore a study of the methods of concentration of the ores from igneous rocks. Processes operating in the magma may cause differentiation and segregation of workable bodies. Deposits so formed, including both oxides and sulphides, are well authenticated, although deposits of sulphides are rare. Low-grade materials of magmatic origin may on weathering become rich

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[1] Harker, Alfred: "The Natural History of Igneous Rocks," pp. 311–332, 1909.

One of the clearest discussions of differentiation of magmas is that by L. V. Pirsson in U. S. Geol. Survey *Bull.* 237, pp. 181–190, 1905.

residual masses, or they may weather and be subsequently reconcentrated by mechanical processes, forming sedimentary beds. Meteoric waters may dissolve the valuable constituents from the solid igneous rock and concentrate them by precipitation in openings. But magmas carry water and other fluids that solidify at low temperatures, and during crystallization these fluids may escape. Coursing through fissures and reacting with rocks, they precipitate metals with which they are charged, and in the higher regions they mingle with ground water, which generally causes further precipitation of mineral matter. Ultimately they may escape as hot springs. The processes by which ore deposits are formed from these igneous emanations are discussed elsewhere in this book.

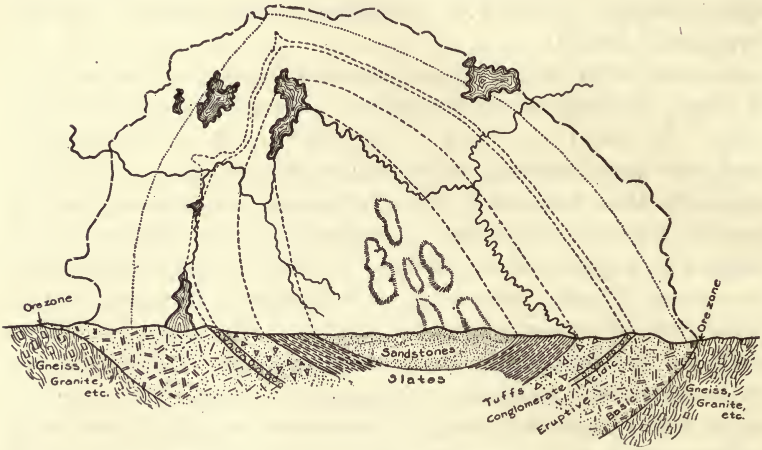

FIG. 7.—Cross-section and plan of part of Sudbury nickel district, Ontario. (*After Coleman, Ontario Bureau of Mines, Canada.*)

Occurrence.—From the foregoing discussion it would be supposed that magmatic segregation would not occur in ordinary surface lavas. These bodies cool quickly, and appreciable segregation rarely takes place in them. Owing to the relief of pressure when they are poured out, steam and other gases which aid diffusion readily escape. At a few places gems and metals are found in surface lavas, such are probably due to magmatic segregation before eruption, but they are of relatively small value. The deep-seated rocks, especially the basic rocks, such as norite, gabbro, and peridotite appear to be especially favorable to magmatic segregation. The more acidic rocks, on the other hand, are more fruitful as sources of epigenetic ores. Lithium, tungsten, tin, and some other elements are characteristically associated with the acidic magmas; nickel, platinum, and chromium are associated with basic or ferromagnesian magmas.[1] Some iron deposits appear to have segregated from moderately acidic rocks.

Gravity and fractional crystallization tend to segregate portions of the magmas at the bottom or on the sides of rock units. Among the deposits found in such positions a conspicuous example is that of the nickel ores of the Sudbury nickeliferous eruptive mass (see Fig. 7). On the other hand, many deposits formed by magmatic segregation are entirely surrounded by the parent rock. Some dikes and flows are essentially all ore or protore. Such bodies are assumed to be the products of magmas as differentiated before extravasation. All the laws governing these localizations have not yet been elucidated.

Composition.—As deposits due to magmatic segregation are igneous rocks, their minerals are exclusively the igneous rock-making minerals and their alteration products. A list of the more important minerals is given below.

acmite
aegirite
albite
allanite
amphiboles
analcite
anorthite
apatite
arfvedsonite
augite
biotite
cancrinite
cassiterite
chalcopyrite
chromite
corundum
cordierite
diallage
diamond
diopside
elæolite
emery
feldspars
fluorite
garnet
gold
graphite
haüynite
hematite
hornblende
hypersthene
ilmenite
iron
leucite
magnetite
melilite
molybdenite
monazite
muscovite
nepheline
noselite
olivine
orthoclase
pentlandite
perofskite
picotite
platinum
pyrite
pyroxenes
pyrrhotite
quartz
riebeckite
rutile
sapphire
silver
sodalite
specularite
spinel
spodumene
titanite
topaz
tourmaline
tridymite
xenotime
zircon

Shape.—Some valuable minerals, like diamonds, sapphires, and rubies, are sparingly disseminated in igneous rocks. In some deposits the rock mass exposed may be essentially homo-

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[1] Washington, H. S.: The Distribution of Elements in Igneous Rocks. Am. Inst. Min. Eng. *Trans.*, vol. 39, p. 735, 1908.

geneous, and any magmatic differentiation must have taken place before the body now exposed came to rest. The entire mass is then the mineral deposit. Such masses obviously may be tabular dikes (like the sapphire deposits at Yogo, Mont.) or irregular stocks (like the Kimberly diamond deposit), or they may be irregularly shaped like any irregular intrusive igneous body. Some deposits of titaniferous magnetite are simply igneous dikes. A deposit that forms only part of the parent rock mass is generally irregular, but some of these also are broadly tabular. In general, however, deposits segregated in the parent magma approach the tabular form less closely than fissure veins or sedimentary beds.

Fig. 8.—Iron ore formed by magmatic segregation, from Iron Lake, Minnesota. Dark is intergrowth of magnetite and ilmenite; light is feldspar. (*After Singewald.*)

Size.—In size the deposits due to magmatic segregation are exceedingly diverse. Among the large ore bodies formed by this process are certain deposits of magnetic iron ores that aggregate millions of tons and the enormous deposits of nickel-copper ores in Sudbury, Ontario. On the other hand, small segregated deposits of chalcopyrite or galena and schlieren[1] of chromite may be too small to be of value.

Texture.—The constituent minerals of these deposits are generally mutually interlocked, like the minerals of granular igneous rocks. In some deposits magnetite, pyrite, olivine, and certain other minerals have crystallized out before the more siliceous minerals, such as feldspar and quartz. If the deposit has been formed by the separation of falling metalliferous crystals, the ore minerals, which are the heavier constituents, should

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[1] *Schlieren* is a German term without an English equivalent, used to describe poorly defined streaks of material formed in or near the border of an igneous mass before the magma came completely to rest. They are even less persistent than most veinlets or gash veins.

be among the first minerals that were formed in the overlying country rock, for they could not fall through a mass already solidified. A study of the relative age of the mineral constituents of the ore and rock, as shown by their contact relations in thin section, is therefore a check on a hypothesis that postulates a genesis by magmatic segregation. It should be noted, however, that segregation may take place prior to crystallization, and that in some ore bodies of this class the ore minerals have crystallized after the gangue minerals and now inclose them (Fig. 8).

Fig. 9.—Section of ore formed by magmatic segregation. Well-shaped crystals of feldspar and quartz, partly dissolved are floated in a matrix of galena.

Although banding is not characteristic of deposits formed by magmatic segregation, some of them—for example, some of the magnetites of New York—show many bands of magnetite alternating with feldspar. The banding is not crustified, however, and this feature, together with the mineral composition, serves to distinguish them from normal fissure veins. The same minerals are found in the ore and in the parent country rock, and as a rule the ore passes into the country rock by a gradual diminution of ore minerals or by an increase in gangue minerals. The zone of gradation between ore and country rock may be very narrow; in some deposits it is less than half an inch wide. Vugs are lacking in this group of deposits, and miarolitic cavities are much less common than in pegmatite veins. The original rock minerals are not hydrothermally altered in these deposits, as they are in the wall rock along veins deposited from thermal waters. As the deposits formed by magmatic segregation are not metasomatic, pseudomorphous replacements are unknown in the original ore. If the sulphide ores inclose well-shaped (idiomorphic) crystals of feldspar (as shown in Fig. 9), there is a very strong probability that the deposit is due to magmatic segregation. If it had been formed along a fissure, the borders of the fissure should cross the crystals of the rock, and if it had been formed by replacement, the boundaries of the rock-making minerals would not everywhere coincide so nearly with the crystal boundaries.[1]

Deposits formed by magmatic segregation, like other igneous rocks, may contain fragments of the rocks invaded by the magma. In some places the parent magmas have doubtless contributed solutions that have deposited veins in fissures. Thus ores formed by magmatic segregation and ores deposited in and along fissures may be closely associated and closely related genetically.

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Deposits Formed by Magmatic Segregation

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CHAPTER IV

PEGMATITES

Occurrence.—In or near deep-seated igneous rocks; many are near the outer margins of intrusives. Where pegmatites intrude sedimentary rocks or schists, they generally follow bedding planes or the planes of schistosity, but locally they cut across such planes.

Composition.—The minerals are essentially the minerals found in igneous rocks, but the range in composition of pegmatites is less than that of the igneous rocks. Feldspar, quartz, and mica are very common constituents. Many rare minerals and gem minerals are found in pegmatites. Metals include tin, tungsten, bismuth, yttrium, thorium, tantalum, and others.

Shape.—Many pegmatites have very irregular outlines, especially those which lie within the parent igneous rock. A large number of pegmatites are rudely tabular. Pipe-like and dendritic bodies are represented.

Size.—Pegmatites range in size from minute bodies to masses that extend over many acres. Where the material has been injected in highly foliated schist, the individual pegmatite sheets may be paper thin. Metalliferous concentrations in pegmatites are generally small.

Texture.—The crystals are usually large and commonly are intergrown as in igneous rocks. Some pegmatites grade into the containing parent rock. Miarolitic cavities are common. Banded or comb structure and openings with crustified bands are developed in some pegmatites, but such features are much less common than in normal ore veins. Fluid inclusions are locally abundant.

Pegmatites are the principal sources of marketable feldspars, quartz, and mica, and they contain also several varieties of gems, among them tourmaline, beryl, and kunzite. They are not important sources of the metals, although they have supplied a little tin, bismuth, and tungsten, as well as the rare metals yttrium, thorium, tantalum, etc. Pegmatites are of great scientific interest, because they resemble in some respects igneous rocks and in other respects certain ore veins.

Eutectics.—Igneous rocks may be regarded as frozen magmas. Rock magmas are not physical mixtures but solutions of substances mutually dissolved. Difficultly fusible materials may be readily fused if mixed together. A familiar example is the formation of a common slag with iron, lime, and silica. Lime (CaO) has a melting point so high that it withstands the great heat of the oxyhydrogen flame when it is used to give a calcium light. Silica (SiO_2) likewise has a high melting point, and for that reason it is used by chemists for "quartz ware" receptacles whose contents must be heated to temperatures above the melting point of common glass. Iron also when pure has a high melting point. These three substances, lime, silica, and iron, if mixed in a blast furnace, form a liquid slag at a moderately low temperature; indeed, one of the common problems of the metallurgist is to bring iron, lime, and silica together cheaply and in the proper proportions so that the valuable metals which they may contain will be separated at a minimum cost for fuel. Together they "melt easily" because they dissolve one another.

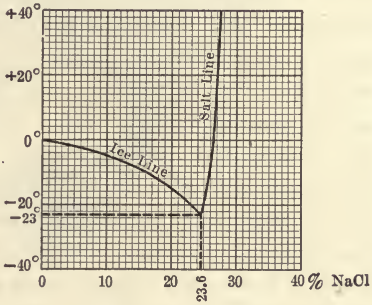

Fig. 10.—Diagram illustrating temperatures of crystallization of salt and ice from salt-water solutions.

The freezing temperature of a solution is generally lower than that of the pure solvent. A solution of sodium chloride in water solidifies at −23°. Pure water solidifies at 0°, and salt solidifies or is precipitated out of solution at a temperature depending on the amount in the solution. The relations are expressed diagrammatically by Fig. 10. As shown by this figure[1] ice will begin to separate from a 5 per cent. salt solution when the solution is cooled to −3.4°. With a 10 per cent. salt solution ice separates at −6°, and with 23.6 per cent. of salt ice solidifies at −23°. The sequence is analogous when solutions containing more than 23.6 per cent. of salt are gradually cooled, but, instead of pure ice, pure salt separates until the residual liquid contains 23.6 per cent. of salt. Ice and salt solidify together at −23°. If the cooling solution has 23.6 per cent. of salt neither ice nor salt separates until the temperature has fallen to −23°, when the whole freezes to a solid mass. No other mixture of water and salt freezes at a lower temperature than this. Hence a solution containing 23.6 per cent. of salt is called a eutectic[2] mixture, and −23° the

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[1] From Mellor, J. W.: "Modern Inorganic Chemistry," p. 161, 1914. Based on determinations made by F. Guthrie in 1875.

[2] *Eutectic* is derived from the Greek words that mean "melt easily." A eutectic mixture or eutectic is not a mineral.

eutectic point. The ice and salt are mutually intergrown, and no matter what the original solution may have been the last fraction to solidify has the same composition and a constant melting point. The crystals of ice may be seen lying in a matrix of salt, more readily if a colored salt like copper sulphate is used.[1]

It has been suggested by Teall[2] and by Vogt[3] that the micropegmatites or intergrowths of orthoclase and quartz that form last in many igneous rocks and fill the interstices between the older crystals are eutectic mixtures, and more recently Day and his associates have investigated many igneous rocks with these premises in view. Teall, from microscopic analyses of such a micropegmatite, regards a mixture of 62.05 per cent. orthoclase and 37.95 per cent. quartz as a possible mixture of maximum solubility; Vogt gives a mixture of 74.25 per cent. orthoclase and 25.75 per cent. quartz. Many pegmatite veins show proportions of quartz and feldspar approximating those suggested by Teall and by Vogt, but the proportions are in general less constant in pegmatite veins than in the micropegmatite that forms the groundmass of some granites and similar rocks. Although there are noteworthy differences in the composition of pegmatites, nevertheless they tend to approach a uniform composition more closely than the normal igneous rocks. The presence of the mineralizers discussed below doubtless influences the chemical systems from which pegmatites are formed; consequently appreciable variations in the composition of the pegmatites should be expected, even in pegmatites that are genetically related to the same rock magma, and there may be considerable variations in a single pegmatite vein.

Agents of Mineralization.—As a rule the crystals of the pegmatites are larger than the crystals of igneous rocks and of ore veins. In ore veins the great masses of solid quartz, when viewed under the microscope, are seen generally to be composed of a large number of small crystals closely interlocking, each having a different optical orientation. On the other hand, a mass of pegmatitic quartz or feldspar commonly shows a uniform optical orientation for each of these two minerals. Élie de Beaumont, Deville, Daubrée, and others, experimenting upon the synthesis of minerals, found that small quantities of H_2O, CO_2, H_3BO_3,

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[1] Mellor, J. W.: "Modern Inorganic Chemistry," pp. 161–162, 1914.

[2] Teall, J. J. H.: "British Petrography," p. 395, 1888.

[3] Vogt, J. H. L.: "Die Silikatschmelzlösungen," part 2, p. 113, 1904.

HCl, HF, and certain other compounds greatly facilitated the crystallization of melts, and the term "mineralizing agents" or "mineralizers" has been applied to these compounds. It is believed that their presence, by decreasing viscosity, aids diffusion and thus favors the development of large crystals. Small amounts of the elements of these agents of crystallization occur in many pegmatites, and they are supposed to have been effective in lowering the point of solidification or precipitation and in promoting diffusion in the magmas.

Some of the minerals that contain the elements of the mineralizers are common in pegmatite veins and in certain deep-seated ore veins. Among the minerals of pegmatites which carry fluorine are topaz, fluorite, fluor-apatite, and some micas. Tourmaline contains boron, and chlorine is contained in chlor-apatite and in some scapolite. Compounds of the rarer elements lithium, beryllium, tungsten and cerium (Fig. 11), seem also to act as agents of mineralization. Minerals containing lithium are lithium, mica, rubellite, amblygonite, and spodumene. Beryl, or aquamarine, contains beryllium. Minerals in pegmatites containing tungsten are wolframite, scheelite, and hübnerite. Columbite and tantalite contain columbium and tantalum. Water is contained in biotite, muscovite, lepidoite, etc.

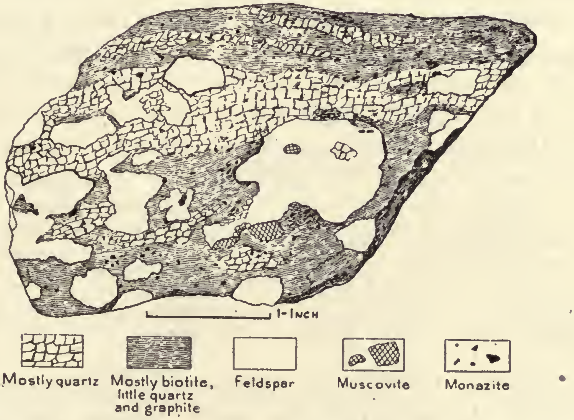

Fig. 11.—Monazite-bearing pegmatite. Shelby, N. C. (*After Sterrett, U. S. Geol. Survey.*)

These minerals, except those containing water, are lacking in some and are found only in relatively small quantities in most pegmatites. Many of them when present were the last minerals formed in the pegmatites, for they line the miarolitic cavities. Fluid inclusions in quartz are common. Larger quantities of water and of these other mobile compounds may have escaped from the cavities after the pegmatite solidified. If not, it must be assumed that the amounts of the mineralizers necessary to accomplish coarse crystallization were in most places small.

Occurrence.—Pegmatites[1] are associated with deep-seated igneous rocks, generally with the siliceous rocks, less commonly also with basic rocks. Rhyolites, basalts, and other surface lavas and intrusive rocks formed near the surface are not accompanied by pegmatites; consequently it is assumed that great pressure is necessary for their genesis. As the deep-seated rocks cool, the end products of crystallization may segregate, and the segregated materials include the more soluble compounds of the magma. Certain investigators have applied to such end products of crystallization the term "granite juice"—a term that implies mobility, which is a striking characteristic of the pegmatitic solutions. The end products are more mobile than the parent magma because of their excess of gases, and if fissures are formed in the solidified portion of the magma or in the country rock near by, the pegmatitic material may be injected into them. Pegmatites may therefore follow cracks, planes of schistosity, or any openings or planes of weakness that were accessible. The pegmatitic solution may even force itself into the surrounding rock, making the opening as well as filling it. To such processes are doubtless due "leaf injections," in which paper-thin sheets of pegmatite alternate with thin sheets of schists. Pegmatites of larger size fill openings and may have

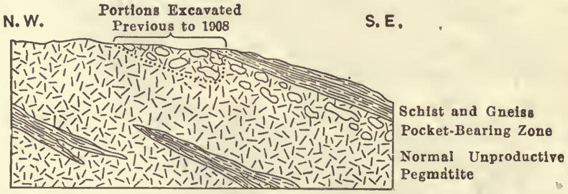

FIG. 12.—Sketch of pegmatite with zone of tourmaline pockets near the top of Mount Mica, Paris, Maine. (*After Bastin, U. S. Geol. Survey.*)

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[1] For a good digest of the literature relating to the origin of pegmatites, see HASTINGS, J. B.: Origin of Pegmatite. Am. Inst. Min. Eng. *Trans.*, vol. 39, pp. 104–128, 1908.

sharp, clean-cut boundaries; still others are segregated in place, without movement of the pegmatitic magma as a mass, and are surrounded by the parent igneous rock and locally grade into it. At many places, however, the pegmatite stuff is forced out of the magma, and crystallizes in fissures and in small cracks in rocks around the parent body. Except in layered rocks pegmatites do not generally occur in parallel or other regular systems but appear to be haphazard.

Composition.—Of the minerals that make up the pegmatites orthoclase and quartz are generally the most abundant, and many pegmatites are composed essentially of these minerals. In others mica appears also, and in still others mica and albite. Though albite is in the main much less abundant in pegmatites than orthoclase, in some of the pegmatites it is the principal feldspar. A pegmatite in Nelson County, Virginia, is composed essentially of apatite and ilmenite.[1] Most pegmatites, however, are composed principally of feldspars and quartz, with very small amounts of one or more of the other minerals listed below. In general the pegmatites are richer in silica than the parent rocks.

acmite
albite
allanite
amphiboles
andalusite
anorthite
apatite
aquamarine
arsenopyrite
augite(?)
beryl
bismuth
bismuthinite
biotite
bornite
calcite
cassiterite
chalcopyrite
chromite(?)
columbite
corundum
diamond
diopside
emerald
emery
fluorite
galena
garnet
gold
graphite
hematite
hornblende
ilmenite
kyanite
lepidolite
magnetite
microcline
molybdenite
monazite
muscovite
orthoclase
pyrite
pyroxenes
pyrrhotite
quartz
rhodochrosite
rhodonite
ruby
rutile
sapphire
scapolite
scheelite
specularite
spinel
spodumene
tantalite
titanite
topaz
tourmaline
wolframite
xenotime
zinc blende

Nearly all the minerals named above have been found in igneous rocks also, but many minerals that occur in igneous rocks have not been reported from pegmatites. Although pegmatites commonly contain many sulphides they are but rarely commercial sources of the metals.

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[1] Watson, T. L.: Occurrence of Rutile in Virginia. *Econ. Geol.*, vol. 2, pp. 492–504, 1907.

Shape.—Many pegmatites are very irregular in shape, especially those remaining in the parent rock, and of these some have weird shapes that are very puzzling. The dendritic mass or branching pipe figured by Butler[1] (see Fig. 13) is believed to have been formed by movement of the pegmatitic solution in a cooling but still viscous mass of the parent magma. Some pegmatites are sheet-like, and some are pipes, long in one and short in two dimensions. The thin, rudely tabular mass is perhaps the most common form.

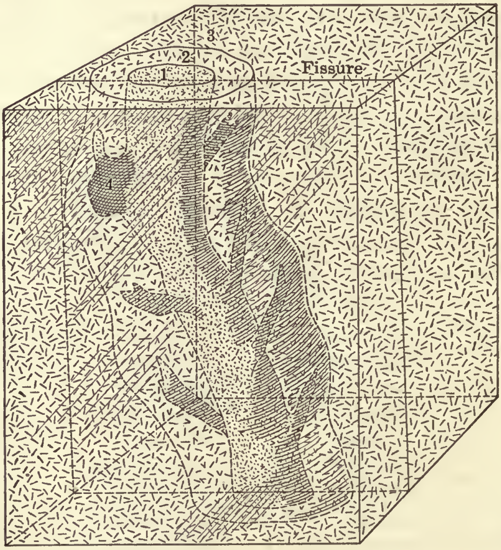

Fig. 13.—Generalized stereogram showing the relation of pegmatitic quartz and altered and mineralized quartz monzonite in the O. K. mine. San Francisco region, Utah. 1. Pipe of quartz; 2, altered monzonite; 3, monzonite; 4, high-grade ore. (*After Butler, U. S. Geol. Survey.*)

Size.—Although pegmatites vary greatly in size, most of those which are commercially valuable are small. Some quarries producing graphic granite, quartz, feldspar, and mica exploit pegmatite masses of considerable size. On the other hand, many of the pegmatite deposits of gems or of rare metals are too small to justify more than crude installations for mining. Some of them are mere pockets; others consist of a few large crystals. A few are large and persistent.

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[1] Butler, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah. U. S. Geol. Survey *Prof. Paper* 80, p. 125, 1913.

Texture.—The crystals of pegmatites are generally large, and some of them are enormous. One crystal of spodumene at the Etta mine, in the Black Hills, is more than 40 feet long, and crystals several inches long are not uncommon. The constituent minerals, as a rule, are intergrown as in granular rocks. Porphyritic texture is rarely developed.

The concentration of elements to form the large crystals in pegmatites is due to diffusion in the liquid magma. A crystal while forming will tend to draw material of the same composition to it. Such attraction is opposed by the viscosity of the magma, which depends on the amount and condition of the included gases.

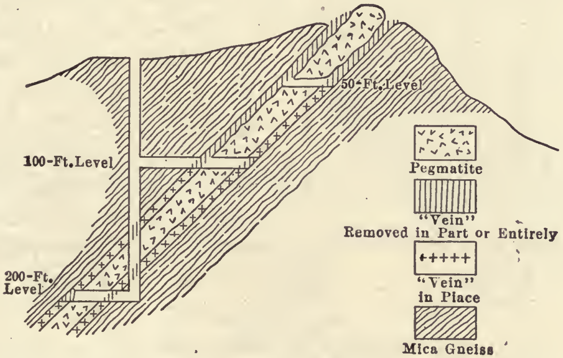

FIG. 14.—Section of pegmatite vein, New York mine, near Custer, S. Dak. (*After Sterrett, U. S. Geol. Survey.*)

In the main the fissures into which the pegmatites were thrust were probably not connected freely with the surface. If there had been such open connection the steam and other mineralizers that facilitated diffusion and the formation of large crystals should have readily escaped, except where the connection was crooked, the depth great, and the pressure correspondingly high. Moreover, if there had been open connection deposition would probably have been effected by circulating solutions moving to the surface, which tend to form the banded structure that is characteristic of fissure veins. Banded structure is relatively rare in pegmatites. In the greater number of pegmatites the structure is hypidiomorphic-granular, like that of most deep-seated igneous rocks. An example of a layered pegmatite may be seen in the New York mica mine, near Custer, S. Dak. (Fig. 14), where a pegmatite vein 30 feet wide intrudes schist, and several feet of mica occurs here and there at the margin of the vein on both the hanging wall and the foot wall[1] (see also Fig. 15). It is probable that in some places the magmas which formed pegmatites also gave off solutions which deposited ore veins.

Gradations.—Van Hise[2] has described a series of pegmatites in the Black Hills, where a granite batholith sends off quartz-feldspar dikes into the surrounding crystalline schists; farther out in the schists these dikes are small and become pegmatites. Still farther out they show a rough concentration of minerals into layers, and farther still true comb structure and ribbon structure. At a yet greater distance feldspar entirely disappears and the openings are filled with ordinary vein quartz. A quartz offshoot of pegmatite is shown in Fig. 16.

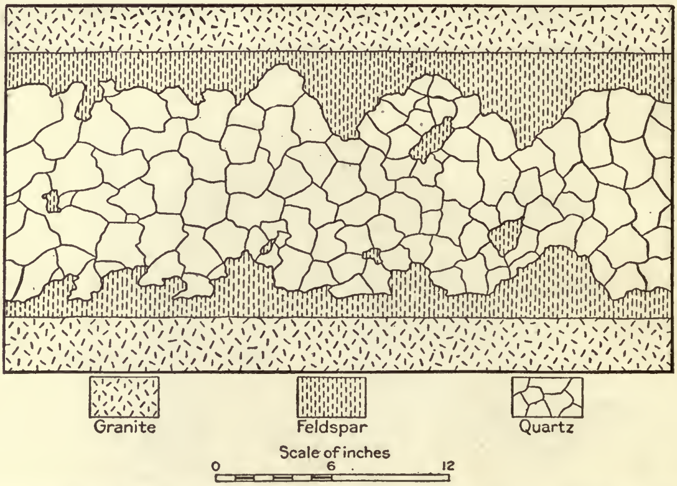

Fig. 15.—Sketch of layered pegmatite dike. (*After Graton, U. S. Geol. Survey.*)

In the Encampment district, Wyoming, Spencer[3] found that coarser pegmatites and also aplite dikes grade into quartz veins.

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[1] Sterrett, D. B.: Mica Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, p. 382, 1909.

[2] Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, p. 724, 1904.

[3] Spencer, A. C.: The Copper Deposits of the Encampment District, Wyoming. U. S. Geol. Survey *Prof. Paper* 25, p. 41, 1904.

In Shasta County, Cal., according to Graton,[1] pegmatite veins grade into quartz veins that carry sulphides.

Pegmatites that grade into gold-bearing quartz veins, however, are surprisingly rare. Spurr[2] has shown that some gold-bearing veins of Silver Peak, Nev., and in Alaska have pegmatitic characteristics, but such examples are not common. In general, normal vein deposits were formed by solutions which were highly aqueous and which normally circulated in openings that connected either directly or by devious routes with the surface of the earth, whereas the pegmatites were deposited by solutions which were much richer in the rock-making constituents other than water, and these solutions in general were not moving freely to the surface.

Temperature of Formation of Pegmatites.—From their associations it is believed that pegmatites are normally formed at high temperatures. This inference is supported by the work of Wright and Larsen,[3] who utilized the discovery of Mügge, namely, that when quartz is heated it suffers at 575° an enantiotropic change to a second phase, called β-quartz by Mügge, and that above 800° it is no longer stable at ordinary pressures but passes into tridymite. The change from the stable form, called α-quartz by Mügge to β-quartz is attended by an abrupt change in the birefringence, circular polarization, and expansion coefficient at that temperature. Cold quartz that was formed above 575° will show certain changes, such as fracturing and irregular twining. Examinations by Wright and Larsen showed that many pegmatites have formed below 575° and some above that temperature.

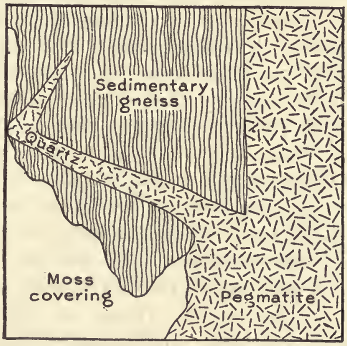

Fig. 16.—Quartz offshoot from pegmatite, Paris, Maine. (*After Bastin, U. S. Geol. Survey.*)

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[1] Graton, L. C.: The Occurrence of Copper in Shasta County, California. U. S. Geol. Survey *Bull.* 430, p. 86, 1910.

[2] Spurr, J. E.: Ore Deposits of the Silver Peak Quadrangle, Nevada. U. S. Geol. Survey *Prof. Paper* 55, pp. 130–156, 1906.

[3] Wright, F. E., and Larsen, E. S.: Quartz as a Geologic Thermometer. *Am. Jour. Sci.*, 4th ser., vol. 27, pp. 421–447, 1909.

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CHAPTER V

CONTACT-METAMORPHIC DEPOSITS

Occurrence.—1. In soluble or replaceable rocks—limestones or calcareous shales,—more rarely in quartzites and in igneous rocks.

2. Near intruding igneous rocks of intermediate or acidic composition, such as diorites, granodiorites, monzonites, granites, or their porphyries; more rarely at contacts of basic rocks, such as gabbros and diabases. Not genetically related to surface lavas or glassy rocks.

3. Most of them touch or lie within a few rods of the outcrops of igneous rocks, but they may be as much as 100 rods away, or rarely farther. Some form broken or disconnected belts around the igneous masses. The ores are generally segregated in irregular bunches or large masses in the contact-metamorphic zones.

Composition.—The minerals are characteristic. The ore is commonly a mixture of silicates intergrown with oxides and sulphides of metals. The metals include copper, iron, zinc, tungsten; more rarely gold, silver and lead.

Shape.—Generally irregular in detail; deposits nearly equidimensional are common; some are rudely tabular; many show gradational boundaries with rocks introduced.

Size.—From bodies yielding a few tons to large masses.

Texture.—The ore minerals are intergrown with the contact-metamorphic silicates. Where shale or other banded rocks are replaced the ore may be banded, but there is no crustified banding. Vugs are rare, if not lacking.

Occurrence.—Contact-metamorphic deposits are formed in intruded rocks by fluids given off by intruding igneous magmas. In general the intruded rock is changed near the contact. Such changes may be small, consisting merely of baking, induration, or vitrification of the intruded rocks, or of recrystallization of their constituent minerals. At many places, however, the changes are extensive, and the zone of altered rock may extend many rods from the intruding mass. The agents[1] that cause changes so intense are believed to be the fluids, probably gases, contained in the intruding magma. If the magmas are intruded near the surface, and especially if the intrusive reaches the surface, the gases more readily escape, either through the molten mass itself or through the fissures in the intruded rock, which normally are

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[1] Lindgren, Waldemar: The Character and Genesis of Certain Contact Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 31, pp. 226–244, 1901.

more open or more numerous at relatively shallow depths, where the overlying load is lighter. Consequently the effects of metamorphism along the contacts of basalts, glassy andesites, and rhyolites are slight, whatever rock they intrude. More intense contact metamorphism, producing the contact-metamorphic deposits of the metals, is associated with the deep-seated granular rocks, such as granites, monzonites, and diorites, and with the deep-seated porphyries, which have a finely crystalline groundmass, rather than with those that have a glassy groundmass.

In general contact metamorphism is more profound along the contacts with intermediate or acidic rocks, such as diorites, monzonites, and granites, than along the contacts of gabbros, diabases, and pyroxenites. But not all granites are bordered by contact-metamorphic zones, even where they intrude rocks favorable for the development of such zones. Some magmas, both acidic and basic, seem poor in fluids, or else they give them up reluctantly.

Of the rocks that may be intruded, limestone is most readily changed and is usually converted into a rock composed of calcite, garnet, diopside, actinolite, tremolite, epidote, magnetite, specularite, and other minerals. Shale likewise changes readily, especially calcareous shale; the same minerals may be developed in shale as in limestone, but the aluminum-rich minerals, such as andalusite, scapolite, and sillimanite, are formed also. All these minerals and many others are formed by replacement of the country rock; the replaced rock may preserve the bedding, jointing, fossils, and some other features of the original rock. If a limestone is metamorphosed all the constituents of certain minerals, such as chalcopyrite, may be added to the rock. For others, such as andradite, certain elements are added from the magma to the elements of the intruded rock. Still others, like calcite, are formed simply by recrystallization of the elements of the limestone.

The changes in a quartzite that is invaded are ordinarily slight compared to those in limestones and in shales. Garnet, usually microscopic, may be developed near the contact. In many places tourmaline is deposited, but this mineral is not confined closely to the contact, being formed to a considerable distance from the intrusive. Tourmaline is not usually abundant in contact-metamorphic deposits but is singularly widespread in certain areas of quartzite intruded by monzonite, as at Philipsburg, Mont.,[1] and in the Coeur d'Alene district, Idaho.[2] Siliceous schists generally are less affected by contact metamorphism than calcareous rock.

Where igneous rocks are intruded extensive garnet zones are rarely developed, but along the fracture planes of the older rock some garnet with tremolite, actinolite, epidote, biotite, and other minerals may be deposited, and locally these minerals may replace the older rock. Contact-metamorphic silicates are developed in igneous rocks at Cananea and Velardeña, Mexico.[3] At Velardeña the metamorphism of igneous rocks is unusually extensive.

Igneous intrusives solidify progressively downward. If suitable channels are provided, solutions from the deeper liquid portions may rise to the solidified portions and profoundly alter them

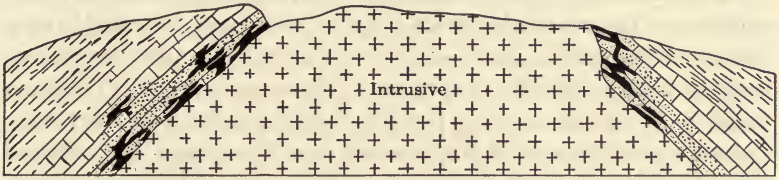

Fig. 17.—Diagram showing relations of contact-metamorphic deposits (black) to contact metamorphic zone (stippled) and to intrusive mass.

Contact-metamorphic ore deposits are portions of the metamorphic zones that contain the metallic minerals in valuable concentrations (see Fig. 17). As a rule they occur only here and there in such zones, and the features that control their localization are often obscure. The more valuable contact-metamorphic ore deposits are generally, though not always, confined to the metamorphic zones in limestones and in calcareous shales, but valuable deposits are not developed in all such zones. Garnetization is erratic, and at many places where sulphides are present they are very irregularly distributed. As a rule contact-

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[1] Emmons, W. H., and Calkins, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, p. 160, 1913.

[2] Ransome, F. L., and Calkins, F. C.: Geology and Ore Deposits of the Coeur d'Alene District, Idaho. U. S. Geol. Survey *Prof. Paper*, 62, p. 101, 1908.

[3] Spurr, J. E., and Garrey, G. H.: Ore Deposits of the Velardeña District, Mexico. *Econ. Geol.*, vol. 3, p. 698, 1908.

metamorphic ores are not of very high grade, but some, even of those that have not been enriched by secondary processes, are extensive and are worked at a profit.

The intruding rocks that cause contact metamorphism in which garnet sulphide ores are developed are in the main of acidic or intermediate composition, and many of them are rather rich in potash. At Cable, Mont., the intruding rocks are quartz monzonite and quartz monzonite porphyry; at Ely, Nev., the agent of metamorphism is a rather acidic, potash-rich monzonite porphyry; at Bullion, Nev., it is granodiorite porphyry; at Bisbee, Ariz., the intruding rocks are granite and granite porphyry; at Cananea, Mexico, quartz porphyry and quartz diorite porphyry.

In the Morenci district, Arizona, the metamorphic effects of the acidic and intermediate rocks may be compared in a single rock mass, which grades from diorite porphyry through monzonite porphyry into granite porphyry. There, as shown by Lindgren (page 376) the monzonitic porphyry and granite porphyry have caused great changes at the contact, but the diorite has affected the intruded rock only slightly. However, not all metamorphosing intrusives are acidic. At Hedley, British Columbia, as shown by Camsell,[1] garnet ores with sulphides and gold have been developed in limestone near gabbro and at Cornwall, Pa., magnetite deposits are developed near diabase.

Some deposits due to contact metamorphism are as much as half a mile from the exposed contacts. A few have been found where no igneous rocks are exposed, but these are presumably above intrusive masses not yet uncovered by erosion. Because not all these deposits are at the contacts they are termed by some investigators "deposits of igneous metamorphism," but this term is not in general use.

Composition.—The following minerals are among those that have been identified in contact-metamorphic zones:

actinolite
albite
allanite
amphiboles
andalusite
andradite
ankerite
anorthite
anthophyllite
apatite
arsenopyrite
augite
axinite
beryl
bismuthinite
biotite
bornite
calcite
cassiterite
chalcopyrite
chlorite
chromite
corundum
cordierite
diopside
dolomite
emerald
emery

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[1] CAMSELL, CHARLES: The Geology and Ore Deposits of the Hedley District, British Columbia. Canada Geol. Survey *Mem.* 2, pp. 164–174, 1910.

epidote
fluorite
forsterite
franklinite
galena
garnet
glaucophane
gold
graphite
grossularite
hematite
honblende
hulsite
humites
ilmenite
ilvaite
jadeite
kyanite
ludwigite
magnetite
microcline
molybdenite
monazite
muscovite
olivine
orthoclase
paigeite
picotite
platinum
pyrite
pyroxenes
pyrrhotite
quartz
rhodonite
ruby
rutile
sapphire
scapolite
scheelite
sericite
sillimanite
specularite
spinel
staurolite
titanite
topaz
tourmaline
tremolite
vesuvianite
willemite
wollastonite
zinc blende
zincite
zoisite

It is noteworthy that although the associations of minerals that make up contact-metamorphic deposits are characteristic if not unique, nearly all the minerals themselves may be formed under other conditions also. Some of them occur in igneous rocks. Others are formed as a result of regional metamorphism, and still others are formed in metalliferous veins. Staurolite, vesuvianite, and wollastonite are probably limited to contact-metamorphic deposits and to deposits formed by dynamic metamorphism. The tellurides and the antimony and arsenic sulphosalts of silver, on the other hand, are rarely developed in contact-metamorphic deposits.

There is strong ground for supposing that some minerals reported to occur in igneous rocks are in the intensely metamorphosed products of fragments of sedimentary rocks caught up in the igneous magmas. This is probably true of andalusite and ilvaite; possibly of actinolite and other minerals. It is noteworthy that the sulphates barite and celestite, which are formed under many conditions, are almost unknown in contact-metamorphic deposits. The veinlets of barite that cut such deposits in some districts are distinctly of later age.

The ores of the contact-metamorphic deposits include (1) iron ore, carrying magnetite and specularite; (2) copper ore, carrying chalcopyrite and bornite; (3) zinc ore, carrying zinc blende; (4) lead ore, carrying galena; and (5) gold ore, carrying gold with quartz, pyrite, arsenopyrite, calcite, or other minerals. A small amount of silver is present in some deposits associated with copper or with gold ores.

Shape and Relation to Fissuring.—At the high temperatures and pressures at which contact-metamorphic deposits are formed, the solutions are capable of entering minute openings, such as cleavage planes of minerals and intergranular spaces. Consequently these deposits are not necessarily related to fissures in the intruded rocks—in fact, most of them seem to be independent of any fissuring that can be recognized after metamorphism. Garnet veins, however, are formed in some regions of contact metamorphism. A short vein of garnet rock with sulphides occurs at Bullion, Nev. (Fig. 18), and garnet veins in limestone are developed at Jarilla and Hachita, N. Mex.[1]

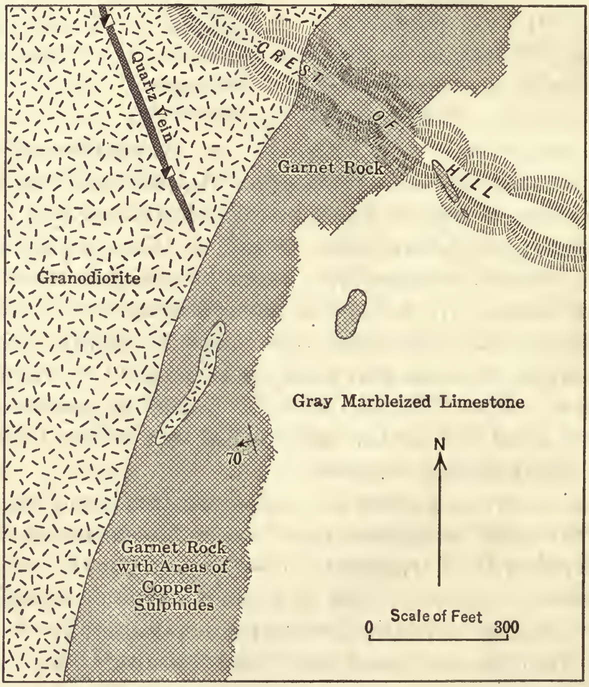

FIG. 18.—Sketch showing the relation of the zone of contact metamorphism to granodiorite and limestone. Bullion District, Nevada.

The solutions, after they lost their power to replace the country rock with garnet and other heavy silicates, must have moved to points of less pressure, away from the magma and generally toward the surface, for the magma was exhaling its compressed gases or liquids wherever they could escape. The solutions that

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[1] LINDGREN, WALDEMAR, GRATON, L. C., and GORDON, C. H.: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68, p. 56, 1910.

escaped from the intrusive mass and the contact-metamorphic zone must have carried with them some lime and large quantities of carbon dioxide removed from the calcerous rocks. Presumably the solutions gathered in fissures or in trunk channels as soon as such openings were encountered, and if they were still charged with the metallic sulphides they may have deposited ores free from the heavy silicates and poor in minerals containing the elements of the "mineralizing" gases. Thus a contact-metamorphic zone may be surrounded by an area in which fissure veins and other deposits not of contact-metamorphic origin have formed (see Fig. 19). Consequently there are gradational phases between contact-metamorphic deposits and veins, some of which contain heavy silicates or other minerals characteristic of contact-metamorphic deposits. Veins of the deep zone that contain heavy silicates and oxides and were formed at high temperature and pressure are discussed on pages 49–61.

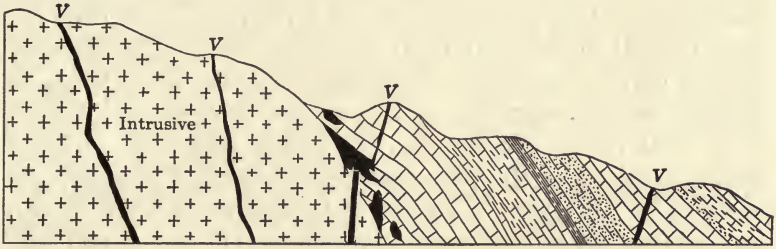

Fig. 19.—Section showing sedimentary rocks intruded by igneous rock, with contact-metamorphic deposits (irregular black areas) and veins.

A few contact-metamorphic deposits are approximately tabular in shape. Where a single bed is replaced, or where, along an intrusive rock, replacement follows the contact closely, the deposits that are formed may be long in two dimensions and fairly uniform in thickness.

Size.—Contact-metamorphic deposits vary greatly in size. Many of the sulphide deposits are merely small concentrations of ore minerals in a gangue of heavy silicates, and the ore body grades into the country rock by decrease in metallic minerals. Some deposits of sulphides in Montana, Nevada, and Arizona have apparently been worked out after a few thousand tons of ore were mined. But other contact-metamorphic deposits are large and have supplied ore for continuous mining operations extending over many years. The irregular character and erratic distribution of these deposits, however, make it necessary to observe caution in estimating ore reserves, and generally for blocking out ore the exposures of such deposits must be closer and more nearly continuous than those of sedimentary deposits or persistent veins. Iron oxide deposits of this class likewise show great variation in size. Several bodies of magnetite in the Philipsburg region, Montana,[1] contained only a few thousand tons. On the other hand, the magnetite bodies that replace limestone at Cornwall, Pa.,[2] are extensive. Perhaps the most extensive deposits of contact-metamorphic iron ore in the United States are those of Iron Springs, Utah,[3] and the Eagle Mountains, California.[4]

Texture.—The texture of contact-metamorphic ore is generally characteristic. As a rule the minerals of the ore of the sulphide and heavy silicate type are intimately interlocked and were formed approximately at the same time. The silicates, such as garnet, vesuvianite, tremolite, diopside, and the micas, and the oxides, magnetite and hematite, are commonly intergrown with pyrite, chalcopyrite, zinc blende, and other sulphides. Residual calcite is almost invariably present. The greasy appearance of the massive garnet and vesuvianite where freshly broken, the feathery texture of ore composed in part of actinolite or tremolite, and the greenish, flaky appearance of ore in which the micas and chlorite predominate are more or less characteristic of the sulphide-silicate rock. The proportions of the contact-metamorphic minerals vary greatly. In some regions there are acres of nearly pure andradite; in others the several minerals occur as small bodies mutually intergrown. Where the ore minerals and the silicates replace shale or slate a banding may be shown, but such texture is pseudomorphous after the rock replaced and is not crustified. Some contact-metamorphic ores contain open spaces, into which well-formed crystals of the heavy

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[1] Emmons, W. H., and Calkins, F. C.: The Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, p. 186, 1912.

[2] Spencer, A. C.: Magnetite Deposits of the Cornwall Type in Pennsylvania. U. S. Geol. Survey *Bull.* 339, p. 74, 1908.

[3] Leith, C. K., and Harder, E. C.: The Iron Ores of the Iron Springs District, Southern Utah. U. S. Geol. Survey *Bull.* 338, 1908.

[4] Harder, E. C.: Iron Ore Deposits of the Eagle Mountains, California. U. S. Geol. Survey *Bull.* 503, 1913.

silicates project; but the crystals that line the spaces are not deposited symmetrically in sheets or crusts, one above another, as is common in ore veins. Many of the open spaces in contact-metamorphic ores are solution cavities from which calcite has been dissolved.

The statement that the minerals of contact-metamorphic deposits are intergrown and contemporaneous, though broadly true, needs amplification. In some deposits the heavy silicate minerals and pyrite appear to have formed before the sulphides pyrrhotite and chalcopyrite, which inclose them and heal fractures in them.

At Dillsburg, Pa., according to Harder,[1] the minerals of the magnetite ore have formed in the following order: garnet, pyrite, pyroxene, magnetite, feldspar, epidote. At many places, as at Ducktown, Tenn., the heavy silicate minerals are intergrown with the sulphides but are also fractured and filled by them. It does not follow that there are two epochs of mineralization, sharply set off one from the other. The period of mineralization may have been continuous,[2] the deposition of the sulphides overlapping to some extent that of the silicates.

Material Added to the Intruded Rock by Contact Metamorphism.—The effects of contact metamorphism are different in different places. The rocks that are invaded differ in composition, and doubtless so also do the solutions that are exhaled by the intruding magma. There are many types of metamorphosed rocks, and these are connected by gradational types. At some places the alteration consists chiefly in recrystallization due to heat and possibly to steam escaping from the intrusive.

On the Mesabi range,[3] east of the town of Mesaba, Minn., the iron-bearing formation is intruded by an immense body of gabbro, and its mineral composition has been profoundly altered over many miles. Rock composed of quartz, iron silicate (greenalite), and iron carbonate has been changed to rock composed of quartz, magnetite, grünerite, actinolite, olivene and augite. Except for decrease of combined water the magnetite rock is

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[1] Harder, E. C.: Structure and Origin of the Magnetite Deposits near Dillsburg, York County, Pennsylvania. *Econ. Geol.*, vol. 5, pp. 599–622, 1910.

[2] Lindgren, Waldemar: "Mineral Deposits," p. 666, 1913.

[3] Leith, C. K.: The Mesabi Iron-Bearing District of Minnesota. U. S. Geol. Survey *Mon.* 43, p. 159, 1903.

essentially similar in chemical composition to the parent greenalite rock.[1]

At a great many places however where sedimentary or other rocks are invaded there have been large additions of material. Examples of several types are discussed below.

Silication with Relatively Small Additions of Materials Other than Silica.—At some places contact metamorphism consists principally in silication of the invaded rocks. At Marysville, Mont., quartz diorite breaks through siliceous shales and impure limestones of Algonkian age. The intruded strata have been greatly changed, chiefly by recrystallization and induration. At distances of 1,000 feet or more from the batholith, according to Barrell,[2] the composition of the strata indicates little or no general accession of material from the magma during metamorphism, but within a variable distance, usually within 600 to 1,000 feet, of the batholith, emanations, largely siliceous, have combined with the lime and other bases, and carbon dioxide has been eliminated.

Development of Magnetite Bodies.—At Cable and Philipsburg, Mont., Paleozoic limestones are intruded by great batholiths of quartz monzonite. Here and there along the borders of the intrusives large masses of magnetite replace the marbleized limestone. The minerals associated with the magnetite are tremolite, green mica, diopside, scapolite, quartz, calcite, pyrite, and pyrrhotite. In the Redemption iron mine, near Philipsburg, ludwigite is intergrown with magnetite.[3] Between Anaconda and Cable there are deposits of magnetite with garnet gangue. At the Cable mine large bodies of relatively pure magnetite are surrounded by coarsely crystalline marble. Similar bodies of ore occur in the Clifton-Morenci district, Arizona, and in many other mining districts in the West. Some of them are utilized by smelters for flux, and some are smelted for iron. Those at Fierro, N. Mex., are among the most valuable deposits of this class that are now utilized.

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[1] Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, 1911. Compare analysis on p. 167 with that on p. 185.

[2] Barrell, Joseph: Geology of the Marysville Mining District, Montana. U. S. Geol. Survey *Prof. Paper* 57, pp. 121–142, 1907.

[3] Emmons, W. H., and Calkins, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, pp. 186, 221–231, 1913.

In the region of Cornwall, Pa.,[1] large deposits of magnetite replace limestones and other calcareous rocks. These deposits have yielded considerable iron ore. The Paleozoic and Mesozoic sedimentary rocks are cut by intrusive diabase, which has probably supplied the solutions that deposited the ores. The iron deposits of Iron Springs, Utah, and the Eagle Mountains, California, have been mentioned.

Development of Zones of Garnet and Other Heavy Silicates.—Garnetization, a relatively intense phase of contact metamorphism, very often attends the intrusion of the granular rocks and deep-seated porphyries. Sulphides are commonly formed here and there in the garnet zones (Fig. 20,*a* and *b*). In the garnetization of limestone much material is added to the country rock. Iron, copper, gold, and silver minerals may be introduced. Silica is often added in large quantities, as well as small amounts of boron, fluorine, and chlorine compounds.

Lindgren[2] has shown quantitatively the changes that have taken place in the limestone of the Clifton-Morenci district, Arizona, where large additions of material have been supplied to the intruded rock by the magma. Over large areas the Modoc limestone has become almost completely changed to lime-iron garnet, with some epidote and magnetite. The limestone contains about 94 per cent. of lime carbonate. When it was changed to garnet rock all the CO_2 must have been expelled and large quantities of SiO_2 and Fe_2O_3 must have been added. The chemical changes were metasomatic, and there was no great increase nor great reduction of volume of the rock intruded. The weights, in grams, of the constituents in 1 cubic centimeter of limestone and of andradite are shown below.

	Limestone	Andradite
CaO	1.52	1.08
SiO_2		1.33
Al_2O_2		0.03
Fe_2O_3		1.18
FeO		0.01
MgO		0.01
H_2O		0.01
CO_2	1.19	
	2.71	3.65

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[1] Spencer, A. C.: Magnetite Deposits of the Cornwall Type in Pennsylvania. U. S. Geol. Survey *Bull.* 359, p. 21, 1908.

[2] Lindgren, Waldemar: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 42, pp. 71, 134, 1905.

If the whole of the CaO in 1 cubic centimeter of $CaCO_3$ has been used to convert the rock into garnet, then this volume becomes about 1.40 cubic centimeters of garnet—that is, the volume is increased nearly one-half during metamorphism. Such an increase, according to Lindgren, has almost certainly not taken place. On the other hand, if there has been no change of volume during the alteration, 0.44 gram of CaO has been carried away together with 1.19 grams of CO_2, while 1.33 grams of SiO_2 and 1.18 grams of Fe_2O_3 have been added.

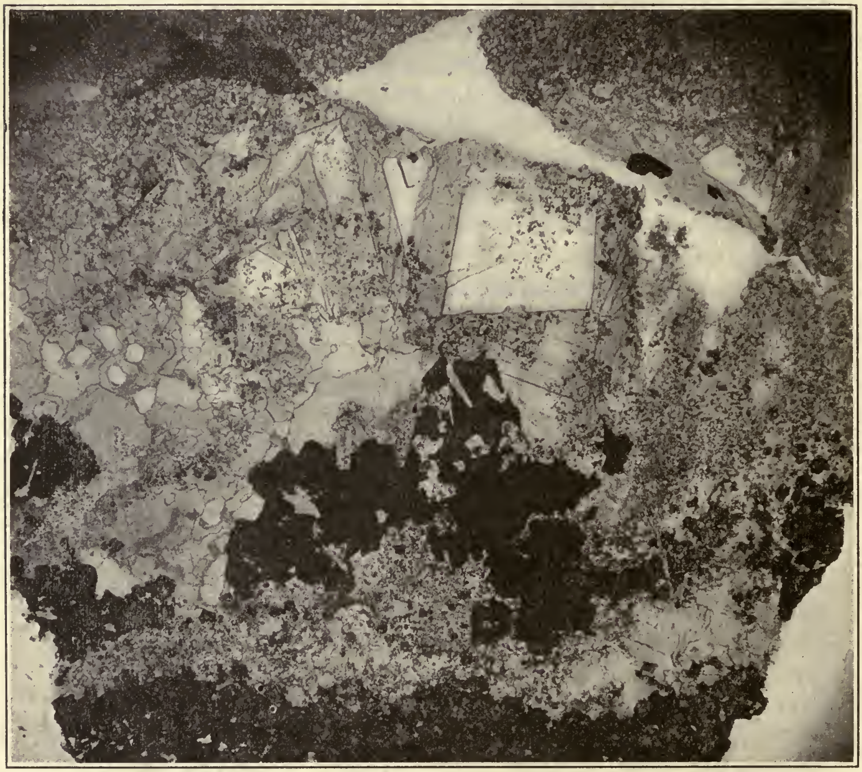

FIG. 20*a*.—Limestone metamorphosed to coarse calcite, garnet, quartz, zinc blende, and chalcopyrite. Magnified about 20 diameters. Morenci, Arizona. (*After Lindgren, U. S. Geol. Survey.*)

Kemp[1] has compared the analyses of unmetamorphosed limestones of Tamaulipas, Mexico, with those of their garnet-rock

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[1] KEMP, J. F.: The Copper Deposits of Tamaulipas, Mexico. Am. Inst. Min. Eng. *Trans.*, vol. 36, pp. 178, 203, 1905.

equivalents and shows that profound changes have been brought about in the composition of the limestones through their intrusion by igneous bodies.

At Philipsburg and Cable, Mont.; Bullion, Lone Mountain, and Golconda, Nev.; Bingham, Utah; Mackay, Idaho; and Cananea, Mexico, the metamorphic zones have received large contributions of various elements from the magmas. At many places the line of contact between the relatively pure limestone and the garnet rock is sharp and distinct, and the transfer of material can not be questioned. The rock mass is continuous, yet the metamorphosed rock is much heavier than the unaltered rock. The mass of evidence indicates that garnetization is usually accompanied by the addition and subtraction of much material.

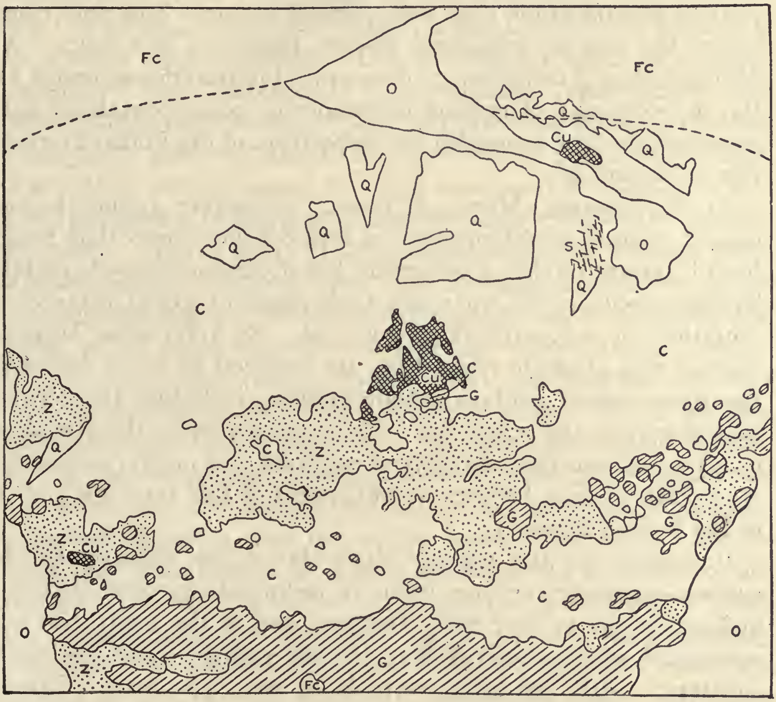

FIG. 20*b*.—Key to Fig. 20*a*. *Fc*, Fine-grained calcite of normal limestone, with dotted line indicating approximate transition to coarse calcite; *C*, coarse-grained calcite; *Q*, quartz; *S*, sericite; *G*, garnet; *Z*, zinc blende; *Cu*, chalcopyrite; *O*, open field. (*After Lindgren, U. S. Geol. Survey.*)

Age of Contact-metamorphic Deposits in the United States.—With respect to age or time of deposition, contact-metamorphic deposits show a wide range. Some of the contact garnet-sulphide ores of Maine[1] are earlier than the period of great regional metamorphism of northern New England and are therefore pre-Silurian and probably Cambrian or pre-Cambrian. In early Cretaceous time there were great intrusions of granodiorites in California, attended by some garnetization. At Bisbee, Ariz.,[2] contact-metamorphic ores were formed in early Mesozoic time, before the Lower Cretaceous, Bisbee, beds were laid down. At Morenci, Ariz.,[3] intrusions of deep-seated porphyries attended by the development of contact-metamorphic zones containing garnet-sulphide ores succeeded the deposition of the Pinkard formation (Cretaceous).

At Philipsburg, Mont., a quartz monzonite batholith has caused contact metamorphism in sedimentary rocks that range from Cambrian to late Cretaceous, but it does not intrude middle Tertiary beds. The intrusion took place in post-Cretaceous, doubtless in very early Tertiary time. At Velardeña, Mexico, dioritic and alaskitic rocks that are believed to be of Miocene age have caused contact metamorphism, including the formation of garnet and sulphides. These are probably the youngest contact-metamorphic deposits of sulphide ores on the continent. No middle or late Tertiary sulphide ores of this type are known in the United States.

In nearly all the regions cited above, the silicate-sulphide contact-metamorphic ores occur in sedimentary rocks that are at least as old as very early Tertiary, and in the main they are associated with intrusives that are not younger than the early Tertiary. Although intrusive rocks of later than early Tertiary age occupy extensive areas in the Western States, contact-metamorphic deposits of sulphide ores are rarely found in genetic association with them, probably because the exposed parts of the younger intrusives have not been so deeply eroded as the intrusives formed earlier.

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[1] Emmons, W. H.: Some Regionally Metamorphosed Ore Deposits and the So-called Segregated Veins. *Econ. Geol.*, vol. 4, pp. 755–781, 1909.

[2] Ransome, F. L.: Geology and Ore Deposits of the Bisbee Quadrangle, Arizona. U. S. Geol. Survey *Prof. Paper* 21, 1904; also U. S. Geol. Survey *Bull.* 529, p. 180, 1913.

[3] Lindgren, Waldemar: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 42, p. 198, 1905.

Depths at Which Contact-metamorphic Ore Deposits Are Formed.—The conditions of great pressure and relatively high temperature under which contact-metamorphic ore deposits are formed rarely prevail simultaneously near the surface. A number of the minerals contained in contact-metamorphic deposits are not ordinarily formed at shallow depths. In the Philipsburg quadrangle, Montana, where quartz monzonites cut through sedimentary rocks that range in age from early Cambrian to late Cretaceous,[1] they have caused a great variety of alteration by contact metamorphism. At some places the early Paleozoic limestones were extensively recrystallized (marbleized) and locally replaced by masses of relatively pure magnetite. At other places they were converted to garnet-epidote rocks, and at still others they were changed to rocks composed of calcite with a small proportion of feathery tremolite evenly distributed through the mass. From a study of the geologic history of the area there is good reason to suppose that these changes took place under as much as 6,000 or 7,000 feet of sedimentary rocks. The younger rocks, which must have been nearer the surface at the time of the intrusion, were metamorphosed also, but they do not contain ore deposits of contact-metamorphic origin. Such changes, therefore, may take place about 1½ miles below the surface. In the Southwest many contact-metamorphic garnet zones are associated with porphyries that have a microcrystalline groundmass and therefore were not cooled quickly like lavas. In the main they have formed at depths less than 1½ miles below the surface. Doubtless a mile of overlying rock is sufficient to meet the requirements for profound metamorphism, and possibly even less is necessary, especially where the intruded rocks are capped by flexible and relatively impervious shale and where extensive fissuring has not supplied easy paths for the escape of the magmatic solutions to the surface. Contact-metamorphic deposits, although showing little evidence of deposition in fractures, are formed in the zone of fracture, yet not at shallow depths.

Function of Mineralizing Agents and Evidence of Their Activity.—The part played by the "mineralizing agents" in the formation of pegmatites is discussed on page 20. These substances render the solutions more liquid and doubtless aid dif-

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[1] EMMONS, W. H., and CALKINS, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, p. 188, 1913.

fusion, which must be effective where large crystals are formed from solution. In the process of contact metamorphism diffusion may play a less important part. Possibly the solutions, after they have accomplished contact metamorphism, gather in the larger openings outside of the principal metamorphic zone and escape to the surface. But such openings do not seem to have been present in all places where contact-metamorphic deposits have been formed, and they may not be essential factors in the process. The exchange of material may take place to some extent by diffusion, the metals passing through the solutions at various rates, while the aqueous solution as a whole does not circulate so freely. Water vapor, boron, fluorine, chlorine, and other volatile substances are believed to take an active part in the transfer of material, and if they do, minerals containing these substances should be expected in the metamorphic zone. Of the minerals identified in contact-metamorphic zones, those containing fluorine are fluor-apatite, fluorite, amblygonite, topaz, and vesuvianite; those containing chlorine are chlor-apatite and scapolite; those containing boron are tourmaline, ludwigite, axinite, hulsite, and paigeite. But in many contact-metamorphic deposits these minerals are rare or absent. Contact-metamorphic minerals of common occurrence that contain combined water are epidote, biotite, chlorite, humite, ilvaite, muscovite, tourmaline, allanite, vesuvianite, and zoisite. As a rule, however, there is relatively little water, combined or not combined, in contact-metamorphic ore, and as such ore contains relatively few cavities which would indicate that water was trapped and remained behind, there is a strong presumption that water or steam has escaped through the outer metamorphosed zone to the surface.

Significance of Mineral Associations and Synthetic Experiments.—Certain minerals, such as quartz, calcite, pyrite, chalcopyrite, and galena, are formed under all conditions of temperature and pressure ranging from those which prevail at great depths to those which prevail at the surface. These are the "persistent" minerals. Other minerals, such as garnet, vesuvianite, tremolite, pyroxene, actinolite, staurolite, tourmaline, and topaz are formed only under conditions of high temperature and pressure. These minerals are confined essentially to rocks or ore deposits formed at the greater depths. Some of these minerals, such as vesuvianite, tourmaline, and staurolite, have not been produced in the laboratory; others, such as specularite and cassiterite, have been produced only at high temperatures or under considerable pressure; still others have been produced at high temperatures in streams of fluoride, or in the presence of steam, boron, or lithium compounds. Such experiments show that normal surface conditions are not favorable for the genesis of these minerals. The same conclusion is illustrated by destructive experiments. When garnet, vesuvianite, and many other minerals of this group are melted and the melts allowed to cool, they will break up into other mineral compounds, among which are anorthite, olivine, and spinel. These and other experiments support the conclusion that contact-metamorphic deposits are formed at high temperatures and pressures.

Temperatures and Conditions of Solution that Form Contact-metamorphic Deposits.—The temperatures of solidification of the deep-seated rocks are in general lower than those of the surface lavas, for the deep-seated rocks retain more water and other gases, which materially lower the point of precipitation. Wright and Larsen[1] have recently made some experiments that have a direct bearing on the problem. Tridymite is formed in the laboratory only at temperatures as high as 800°C. At lower temperatures quartz is formed, but that which is formed above 575° is of the trapezohedral-hemihedral variety, while that formed below 575° is probably of the trapezohedral-tetartohedral variety. The two varieties of quartz show consistent differences in the maximum double refraction and other properties. Tridymite is never formed under the conditions that prevail at great depths but is peculiar to surface lavas. Some of the quartz of contact-metamorphic deposits is of the variety formed at temperatures below 575°C.

Some of the magmas when thrust into the zone where contact-metamorphic deposits are formed must be at least as hot as the lavas that reach the surface. It seems, therefore, that these magmas must cool through a considerable range before they solidify. As the conductivity of rocks is slight, the process of cooling must be slow; consequently there is a long period of sweating before solidification during which contact-metamorphic processes may operate. The solutions pressing outward from the magma at the time of intrusion are probably above the critical

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[1] Wright, F. E., and Larsen, E. S.: Quartz as a Geologic Thermometer. *Am. Jour. Sci.,* 4th ser., vol. 27, pp. 421–447, 1909.

temperature, which for pure water is 358°C. The facts above noted suggest the probability that the solutions causing contact metamorphism are in part in the gaseous state. The competency of the solutions to penetrate minute openings, as indicated by the fact that contact-metamorphic deposits are independent of well-defined fissures, may be due to their gaseous properties.

Fissuring During Contact Metamorphism.—Deep-lying igneous bodies cool slowly. During the period of cooling fracturing and fissuring may attend metallization. The garnet contact rock, wherever it is formed, is relatively impermeable, and unless it is fractured the transfer of material will tend to follow other paths. But fissuring attending the movements of the magma may brecciate the garnet rock and any small dike-like apophyses of the magma which, owing to their smaller size and relatively large surface of radiation, have already become solid. Such movements are illustrated at the Cable mine (see Fig. 21), some 15 miles west of Anaconda, Mont., where Paleozoic limestone and shales are cut by intrusive granite (quartz monzonite) that sends out small apophyses into the sedimentary rocks. Along the contact great angular blocks of granite and of garnet rock are surrounded by material composed of coarse calcite, pyrite, chalcopyrite, pyrrhotite, and magnetite. The relation as indicated by Fig. 21 shows that the metamorphism and extensive recrystallization of calcite and other minerals continued after the garnet rock had formed and after the small apophyses of granite had solidified and had been fractured. As already stated,

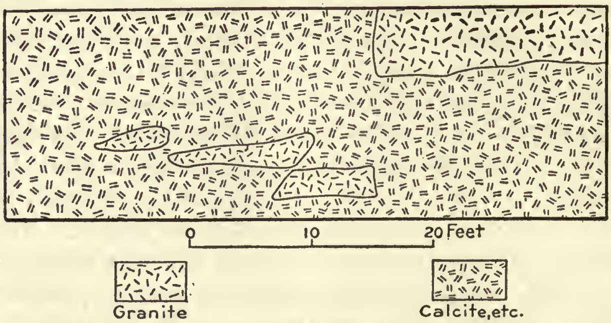

Fig. 21.—Vertical section in Cable mine, near Anaconda, Mont., showing recrystallization of limestone after faulting of granite dike. The dike is an offshoot of granite that caused contact metamorphism.

fissuring, though it may be a contemporaneous incident, is not a necessary condition for contact metamorphism.

Endomorphic Changes.—At some places near intrusive contacts the composition of the intruding rock has changed, presumably as a result of absorption of the rock intruded. Such changes are termed endomorphic. Doubtless endomorphism is an effective process under conditions that prevail at very great depths. Perhaps chemical analyses of selected specimens would show that the intrusive rocks along the contacts absorb lime and aluminum from the intruded rock. At some places fragments of the intruded sediments have probably been completely absorbed.[1] In general, however, in the ore-bearing contact-metamorphic zones there are sharp contacts between the igneous bodies that caused the metamorphism and the intruded rocks, rather than broad zones of material in which igneous rocks and molten sediments are mingled.

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[1] Daly, R. A.: "Igneous Rocks and Their Origin," pp. 216–219, 345, 1914.

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CHAPTER VI

DEPOSITS OF THE DEEP VEIN ZONE

Occurrence.—Found generally in or near intrusive bodies of deep-seated igneous rocks that have been deeply eroded. Not genetically related to surface lavas and intrusives formed near the surface. Rarely found in the younger rocks.

Composition.—The minerals are approximately the same as those formed in contact-metamorphic deposits, but quartz is as a rule more abundant. Gangue minerals include garnet, amphiboles, pyroxenes, and micas. Gangue minerals containing elements of the "agents of mineralization" are commonly present. The simple sulphides of the metals are frequently associated with metallic oxides. Gold, tin, iron, zinc and copper are the most important metals in these deposits. Tungsten and molybdenum also are present in a few of the veins of the deep zone.

Shape.—Some of the deposits are tabular; others are of irregular shape. Stockworks and stringer leads are developed. The large, regular tabular bodies, which predominate in the group of deposits formed nearer the surface, are represented but are proportionately less numerous in the deep-vein zone. Sheeted zones, bedding-plane deposits, saddles, and anticlinal deposits are developed.

Size.—Many of the individual deposits are small; some are large.

Texture.—The lodes are commonly banded. Vugs are locally present. Fluid inclusions are common. Where banded rocks are replaced by ore, the ore may retain the banding. Comb quartz and symmetrical crustification are not unknown, but these features are not so conspicuously developed as in deposits that were formed nearer the surface. Disseminated ore may be formed.

General Features.—Deposits of the deep vein zone are formed at high temperature and under great pressure, in and along fissures or other openings. Although this group is represented by numerous valuable deposits in the United States, it is as a whole less important economically than the group of deposits formed at moderate depth and lower temperature. Ore veins are more commonly formed relatively near the surface, where rocks are more easily fractured and where ascending solutions are more readily cooled in part by mingling with cold surface waters. The Cornwall tin and copper deposits, which are among the most notable examples of the deep veins, have been enormously productive. In the United States the gold veins of the Appalachian region and the Homestake ore bodies of the Black Hills are the best-known representatives.

Aside from economic considerations this class of ore deposits is of great scientific interest,[1] for it supplies a connecting link between pegmatite veins and contact-metamorphic deposits, on one hand, and ores that are formed in and along fissures at moderate depth, on the other. Deposits of the deep zone, because they were formed at high temperatures, are allied mineralogically to contact-metamorphic deposits and to pegmatites; because they were formed in and along fissures, they are allied to vein deposits formed near the surface.

Occurrence.—Although the deposits of the deep vein zone are closely allied mineralogically to the contact-metamorphic deposits, they differ from that group, in that they are clearly related to easily recognized fissures or other openings and are confined to areas where fracturing has occurred before they were formed. As a rule the wall rock is extensively replaced by ore, but such replacement is not so extensive as to obliterate the relationship of these deposits to openings in rocks.

The veins are in or near igneous rocks and probably have been deposited by solutions that were exhaled by the cooling magmas. Some of them cut the parent rock and presumably were deposited soon after the rock had become rigid enough to break, by solutions from a lower portion of the magma not yet solidified. These deposits are not genetically related to lavas or to superficial intrusives, because pressures are moderate where such rocks are formed. Many deposits of this group are in or around granitic rocks, but the intrusive basic rocks less commonly supply the conditions necessary for their formation.

Composition.—Deposits of the deep zone carry gold, tin, copper, iron, tungsten, and other metals. Manganese is rare compared with the amounts found in lodes formed at moderate depths. The deposits contain a large number of minerals, most of which are found also in contact-metamorphic deposits. The commonest of these are garnet, amphiboles, pyroxene, tourmaline, and micas. The sulphides include pyrite, chalcopyrite, pyrrhotite, and arsenopyrite. Topaz, magnetite, ilmenite, specularite, gold, cassiterite, wolframite, and molybdenite are

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[1] Lindgren, Waldemar: The Relation of Ore Deposition to Physical Conditions. *Econ. Geol.*, vol. 2, pp. 105–127, 1907.

developed also. Barite and other sulphates are very rare or absent. The principal minerals are listed below.

albite
amphiboles
andradite
anhydrite
ankerite
apatite
arsenopyrite
bismuthinite
biotite
bornite
calcite
cassiterite
chalcopyrite
chlorite
cinnabar
cryolite
diopside
dolomite
epidote
fluorite
gahnite
galena
garnet
gold
graphite
hematite
hornblende
ilmenite
lepidolite
magnetite
molybdenite
muscovite
orthoclase
platinum
pyrite
pyrrhotite
quartz
rutile
scapolite
scheelite
sericite
siderite
silver
spinel
specularite
stibnite
tellurides (rare)
topaz
tourmaline
tremolite
willemite
wolframite
zinc blende
zincite
zoisite

These minerals may be deposited in open spaces or they may be formed by replacement of the wall rock. It is not everywhere possible to determine just what portion of a deposit has filled an open space and what portion has replaced the wall rock, but in some ores the texture of the wall rock, bedding planes, jointing, mineral boundaries, etc., are preserved in the deposit after the chemical and mineral composition has been changed. The crystals of certain gangue minerals of deposits of the deep vein zone are likely to be larger than those of deposits formed by hot waters near the surface. Thus the crystals of muscovite in greisen[1] are much larger than the crystals of sericite in veins formed at moderate depths. Replacement processes are discussed on pages 218–229.

Shape.—Because they are formed in and along great fissures some of the deposits of this group are broadly tabular. Generally the country rock along a fissure is replaced by ore and the boundaries are irregular in detail. Where the fissures are small, closely spaced, and not parallel, and where the country rock between the fissures has been partly replaced, a large, irregular, and generally low-grade deposit may be formed. Examples are the stockworks[2] of Altenberg, Saxony, and the igneous boss,

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[1] Greisen is altered granite along tin veins. It has been recrystallized and metamorphosed by hot waters. It contains mica, topaz, quartz, and cassiterite.

[2] A stockwork is a deposit made up of many small, closely spaced, irregular veins, with mineralized country rock between. The length of the deposit is not much greater than its width.

containing closely spaced tin veins, at Zinnwald, near by. The irregular deposits in schist in the Appalachian gold belt are figured on page 55.

Size.—Many of the deposits of this class are small, but even the small deposits may be so closely spaced that considerable bodies of rock are workable. Some of the deep vein deposits, however, are large. The tin deposits of the Cornwall peninsula, England—for example, the Dolcoath lode—are very extensive both vertically and along the strike. The Homestake lode in the Black Hills, South Dakota, is one of the greatest gold deposits in the world. Some of the deposits of this group that are worked in the southern Appalachians are small and if they were not closely spaced would be of comparatively little value.

Texture.—Quartz is abundant in many deposits of the deep zones. Much of it contains fluid inclusions with gas bubbles and associated solids. Quartz crystals may project into open spaces or vugs, but the comb structure in which long parallel crystals of quartz alternate with layers of sulphides and other minerals, characteristically developed in open spaces near the surface, is less common in the deep vein zone. In many deposits the quartz occurs as irregular interlocking grains, like the minerals of contact-metamorphic deposits and some igneous rocks. In some, however, it is banded with other minerals. Garnet is not everywhere developed, but in some veins it is abundant. Generally it shows crystal outlines. In some deposits, as in the Lockhart vein, Dahlonega, Ga..[1] garnet is banded with quartz (Fig. 22).

The filled portions of the lodes may differ in mineral composition from the portions that have been deposited by replacement. In the replacement of the walls the heavy silicates may be abundantly developed, but quartz is generally more abundant in the part that represents a former open space. Some of the fractures that have been filled are small and do not continue regularly very far in any direction, and in many places they are arranged as networks of small fractures. Some of them may be mere cooling cracks, but most of them are probably due to relief of stresses. The alterations of the wall rocks, though sometimes more intense, are generally not so extensive as in deposits formed near the surface, where rocks are more readily shattered.

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[1] LINDGREN, WALDEMAR: The Gold Deposits of Dahlonega, Ga. U. S. Geol. Survey *Bull.* 293, p. 126, 1906.

Depth of Formation.—The basis for classifying the deep vein deposits and the two groups next discussed is the depth at which the deposits were formed. This distinction is warranted, because depth in a large measure controls the temperature and pressure and to some extent the character of the openings and the nature of replacement. Moreover, there is little exact information as to the temperature and pressure prevailing at the time the deposits were formed. If knowledge of the geologic history of a region that contains ore deposits is adequate, a reasonably accurate estimate may be made of the depth of formation. Depth, however, is not the only factor that influences the temperature and pressure. The nature of the fissures and especially the character of the rock overlying the deposits at the time of

Fig. 22.—Ore from the Lockhart mine, Dahlonega, Georgia, showing quartz with streaks of garnet, dark green mica and hornblend. (*After Lindgren, U. S. Geol. Survey.*)

their formation are also to be considered. In a fissure that extends freely to the surface the pressure is hydrostatic and will not be greater than the weight of a column of water as high as the place of deposition is deep. Where openings are connected freely with the surface, solutions at temperatures above the boiling point at that pressure could not persist; the water would become steam and escape. On the other hand, in openings that are not connected with the surface the pressure is limited only by the crushing strength of the rocks, and the temperature could be correspondingly high. Therefore, deposits of this class, which are normally formed at great depths, may under some conditions be formed nearer the surface. Some of these deposits, especially where the containing rock is capped with shale, a rock that is not readily fractured and that is relatively impermeable to solutions, may form within 4,000 or 5,000 feet of the surface or even less, but it is believed that most deposits of this group are formed at depths of more than a mile. At Philipsburg, Mont.,[1] some veins of this group were formed about 7,000 feet below the surface at the time of their deposition. In the southern Appalachian gold belt deposits of this class were probably formed 15,000 feet or more below the surface.[2]

Origin of Openings.—Some of the openings that have been filled in the deep zone have doubtless been formed by the relief of compressive stresses; others are in weak rocks and have been filled at great depth, probably where the pressure would quickly close any large openings. In the southern Appalachians,[3] where the veins of this group are typically developed, as stated above, probably more than 15,000 feet of overlying rock has been eroded since the deposits were formed. The nature of the rocks fractured and the mass of the overlying rock seem to have prevented the formation of long, continuous openings. Some of the deposits are in schist, and generally such rocks do not have great strength. It has been doubted whether spaces at depths so great could have remained open long, and they must have been filled quickly. Becker, in his discussion of the fissures filled by

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[1] Emmons, W. H., and Calkins, F. C.: The Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, p. 188, 1912.

[2] Lindgren, Waldemar: The Gold Deposits of Dahlonega, Georgia. U. S. Geol. Survey *Bull.* 293, p. 59, 1906.

[3] Becker, G. F.: Gold Fields of the Southern Appalachians. U. S. Geol. Survey, *Sixteenth Ann. Rept.*, part 3, pp. 251–331, 1895.

such veins, suggests that the force of crystallization of the minerals contained has pushed the vein walls apart, widening thin fissures as they were filled (see page 176). It has been suggested by Graton[1] that the mineral-bearing solutions were injected under pressure that originated in the intrusive magma from which the solutions were derived. He believes that the bodies of quartz did not solidify in open spaces of corresponding dimensions which were ready to receive the solutions; but that the solutions, pushing their way along what may in many places have been the merest cracks, forced the walls apart and made the receptacles in which their load was deposited. The force of crystallization[2] may have aided somewhat in expanding the

Fig. 23.—Vertical section in Schlegelmilch mine, York County, South Carolina, showing lenticular bodies of quartz in amphibolite schist. (*After Graton, U. S. Geol. Survey.*)

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[1] Graton, L. C.: Reconnaissance of Some Gold and Tin Deposits in the Southern Appalachians. U. S. Geol. Survey *Bull.* 293, p. 60, 1906.

[2] Dunn, E. J.: Reports on the Bendigo Gold Fields, p. 25. Victoria Dept. Mines, 1896. Becker, G. F., and Daly, R. A.: The Linear Force of Growing Crystals. Washington Acad. Sci. *Proc.*, vol. 6, pp. 283–288.

openings, but according to Graton the principal factor was the pressure under which the solutions reached the zone of deposition. The structure of these interfoliated veins is indicated by Fig. 23.

Connection with the Surface at the Time of Deposition.—If it is assumed that some of the deposits of the deep zone are related to openings which were formed as a result of pressures that originated in the magmas, and that such pressures in some places exceeded those of the hydrostatic head at the same depths, it is necessary to assume also that the systems of openings did not connect freely with the surface at the time of deposition. If the spent solutions escaped after they had deposited their mineral load, it was through small spaces such as capillary openings, or along minute cracks where friction with the walls served to retard or hold back the magmatic waters. Otherwise the pressure would have been hydrostatic. Under such conditions there could hardly have been a really active circulation of water, and consequently crustified banding, which normally is best developed in veins deposited by freely circulating waters, is not so conspicuously shown.

In the Philipsburg quadrangle, Montana,[1] there are certain gold-bearing veins that carry specularite and pyrrhotite; in the same rocks and at approximately the same elevations are other veins that do not carry minerals of the deep zone. Still other veins near by, formed at the same time and under approximately the same load of overlying rocks, carry tourmaline, quartz, and gold. Pyrrhotite, specularite, and tourmaline are indicative of deposition under high temperature and great pressure. It has been suggested that the lodes which carry the high-temperature minerals were probably formed in fissures that did not extend to the surface, and that the solutions which deposited them were under pressures that exceeded those of the hydrostatic head. Some of the veins near Philipsburg, which do not carry minerals characteristic of deep-seated deposits, were formed at the same depth as the specularite-gold and tourmaline-gold deposits, but the greater persistence of the veins along both dip and strike, their more nearly tabular form, and their banded and crustified texture are features supporting the hypothesis that these fissures were connected with the surface at the time they were formed and that their ores were deposited by circu-

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[1] Emmons, W. H., and Calkins, F. C.: *Op. cit.*, p. 188.

lating waters under hydrostatic head. Both groups of veins were probably formed some 6,000 or 7,000 feet below the surface at the time of deposition. The conditions necessary for the development of the minerals of the deep zone might exist even nearer the surface, in places where the seats of deposition are not connected with the surface by fissures (Fig. 24). But owing to the more extensive fracturing under the lighter load near the surface, such conditions are exceptional.

Function of Mineralizers.—Among the minerals of the deep vein zone are many which contain fluorine, chlorine, boron, lithium, or other elements that enter into the composition of the compounds which have been called the mineralizing agents. These elements, except fluorine, are found in few primary ores in the vein deposits formed under conditions that prevail at moderate and shallow depths. It is believed that they promote diffusion, and owing to the low critical temperatures of many of the compounds that contain them these compounds remain longer in the gaseous state. The mineralizers probably give the solutions greater power to penetrate minute openings and to replace relatively impermeable wall rocks. In the deep zones, where pressures are high and connections with the surface are less direct, the elements of the mineralizers are likely to be fixed in stable mineral compounds, but in the deposits formed at moderate or shallow depth they escape more readily to the surface.

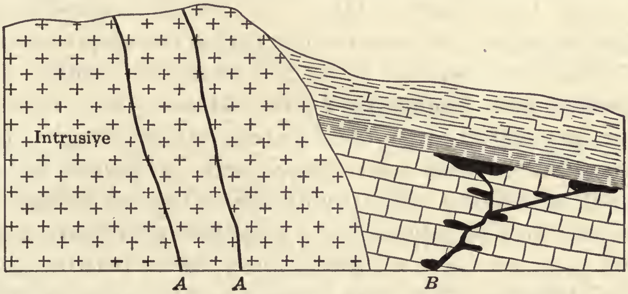

Fig. 24.—Section showing veins of the deep zone type, (*B*) in an area containing veins formed at moderate depths, (*A*).

Age of Deposits of the Deep Zone.—The deposits of this group are formed under conditions of pressure which at the time of deposition existed normally at depths more than a mile below the surface. The deposits therefore generally occur in rocks that have been buried under a mile or more of later rocks or in intrusive masses associated with such rocks. The sedimentary rocks which have been so deeply buried are in the main the older rocks. Lindgren[1] has brought out these relations in his analysis of the gold production of North America.

The deposits of this group are found in the pre-Cambrian and early Paleozoic rocks and in or associated with Mesozoic and early Tertiary intrusive rocks, more commonly than with the middle and late Tertiary intrusives, which in few places have been eroded deeply enough to expose such deposits. Many ore bodies in the older rocks, formed at moderate depth and at low pressure were subsequently buried and therefore do not exhibit any of the features of the deposits of the deep zone. Furthermore, many deposits in ancient rocks have been formed in late periods near the surface. Many ore deposits inclosed in pre-Cambrian rocks are associated with Tertiary eruptives and have all the features of deposits formed at moderate depth.

Gradations into Pegmatite Veins.—Many veins of the deep zone are associated with deep-seated intrusive rocks around which pegmatites seem not to have been developed, but some are closely associated with pegmatites. Typical feldspar pegmatites that may be followed into profitable gold-bearing quartz veins are rare, yet there are gradational phases between the two classes of deposits. The data bearing on the origin of the pegmatites, especially on their gradation into gold-bearing and other quartz veins, have been summarized and discussed by Spurr.[2] There is much evidence to show that in certain areas such as the Silver Peak district, Nevada, and the Yukon region, Alaska, the gold-bearing veins and the pegmatites are deposited by solutions originating from the same magmas.

On Mineral Ridge, near Silver Peak, early Paleozoic strata are complexly injected by granitic rocks that are probably of late Jurassic or early Cretaceous age; at some places these rocks are covered by Tertiary lavas and sedimentary rocks, which, however, do not contain deposits of the metals. The granitic rocks grade into alaskites (rocks containing quartz and alkali feldspar but free or nearly free from other minerals). Some of the

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[1] LINDGREN, WALDEMAR: The Geologic Features of the Gold Production of North America. Am. Inst. Min. Eng. *Trans.*, vol. 33, pp. 790–844, 1902. Metallogenetic Epochs. *Econ. Geol.*, vol. 4, pp. 409–420, 1909.

[2] SPURR, J. E.: The Ore Deposits of the Silver Peak Quadrangle, Nevada. U. S. Geol. Survey *Prof. Paper* 55, p. 129, 1906.

alaskite carries small but appreciable quantities of gold. By diminution of feldspar some of the alaskites grade into pure quartz veins. The quartz is full of fluid inclusions. In the Drinkwater ore zone (Fig. 25) the calcareous country rock surrounding bodies of quartz and also that surrounding bodies of alaskite is similarly metamorphosed, and near the contacts hornblende, epidote, quartz, and feldspar have been developed by contact-metamorphic processes. Iron oxides and sulphides are present in the ore.

Gradation into Deposits Formed by Hot Solutions at Moderate Depths.—A classification of ore deposits is valuable principally as a convenient instrument for purposes of description, comparison, and study. The several classes are connected by gradational types, and nowhere is this relationship more marked than at the hypothetical line separating the deposits of the deep zone from deposits formed by hot waters at moderate depths. Possibly a separation between the two groups should be made on the basis of pressure—magmatic or hydrostatic—for many of the deposits of the deep zone were formed in openings that did not connect freely with the surface and under pressure that probably originated in the magma, whereas most ore bodies formed at moderate depth were deposited in openings or systems of openings that presumably were connected freely with the surface at the time the solutions filled them and therefore permitted the more ready escape of spent solutions and gases. However, some of the most valuable ore bodies that carry the minerals of the deep zone in typical development were formed in and along strong, persistent, and nearly vertical fissures. It is probable

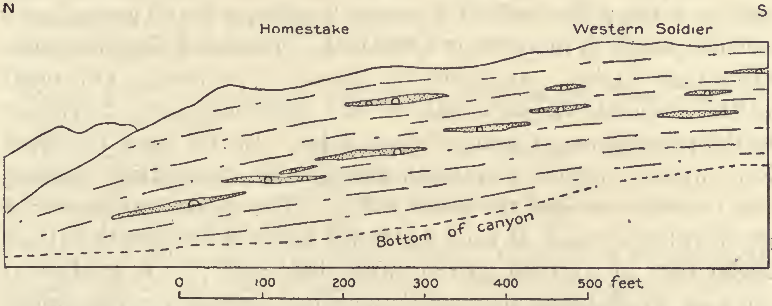

FIG. 25.—Sketch of canyon wall east of Drinkwater mine. Silverpeak quadrangle, Nevada, showing quartz lenses in alaskite.

that such fissures either extended to the surface themselves or connected with other fissures that extended to the surface at the time of deposition.

Some of the lodes of Cornwall—for example, the Standard lode, St. Ives Consols—have been followed down their nearly vertical dip for hundreds of feet. The Dolcoath lode extends in depth 3,000 feet or more. These lodes persist also along the strike and must have been deposited along fissures that had great vertical range. The minerals of the ore include cassiterite and tourmaline, an association which suggests high temperature and pressure.

In the Coeur D'Alene district, Idaho,[1] a thick series of quartzose sedimentary rocks of pre-Cambrian age is intruded by great masses of monzonite and syenite. The sedimentary rocks are cut by persistent lead-silver lodes. Some of them have been explored along the strike for nearly 2 miles, and the group has a vertical range of more than 4,000 feet. The lodes dip at moderately high angles. As shown by Ransome, pyrrhotite and magnetite, minerals characteristic of the deep zone, are developed in the primary ore of some of these lodes. In the Tiger-Poorman lode, which is explored on the lowest level in the district, pyrrhotite increases toward the lower levels. The Tiger-Poorman is of good width, extends at least 4,000 feet along the strike, is at least 2,000 feet in vertical extent, and dips 80°. It is a sheeted zone of overlapping fissures along which extensive replacement has occurred. If before erosion the Tiger-Poorman lode extended upward as far as the apex of other veins near by, the pyrrhotite ore in it was formed at least 4,000 feet below the surface.

Some lodes in the Philipsburg quadrangle, Montana, such as the Sunrise, at Henderson, carry pyrrhotite in variable amounts, and these deposits seem to have been formed at lower temperature and pressure than the pyrrhotite-specularite veins mentioned above. Pyrrhotite is present also in some of the deep veins of California but is not abundant nor widespread. There is much evidence, therefore, that pyrrhotite and probably magnetite also are minerals that link veins of the deep zone to those formed at moderate depth. Like garnet, they are stable under the deep-seated conditions, but their range is somewhat greater than that of garnet and other heavy silicates.

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Gradation into Contact Metamorphic Deposits.—Veins of the deep zone grade also into contact metamorphic deposits. In some districts the mineral composition of the veins changes toward metamorphic zones, magnetite and pyrrhotite becoming more abundant in the veins that are situated nearer the contacts while in the deposits of contact metamorphic origin magnetite, pyrrhotite, and heavy silicates are present in force. In the Iron Springs deposits, Utah,[1] veins and breccia deposits in andesite extend into the larger bodies of ore developed by metamorphism of sedimentary rocks.

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CHAPTER VII

DEPOSITS FORMED AT MODERATE DEPTHS BY HOT SOLUTIONS

Occurrence.—In or near igneous rocks; most of them are near intrusive rocks.

Composition.—Contain a great variety of minerals. Complex sulphosalts of antimony and arsenic are common; metals include copper, silver, gold, lead, zinc, arsenic, antimony, subordinately nickel, cobalt, bismuth, tungsten, etc.

Shape.—The deposits are in the main tabular bodies or combinations of tabular bodies. Sheeted zones, fracture zones, stockworks, and pipes are developed. In limestone many of the ore bodies are chambers. "Saddle reefs" and bedding-plane deposits are developed.

Size.—Some of the ore bodies are large; many are small.

Texture.—The veins that fill fissures are generally banded, and in them comb structure and drusy cavities with symmetrical crustified banding are common. The ore which replaces the wall rocks does not form crusts but may be banded. Pseudomorphous replacement of shales, schists, or other banded rocks will also give banded ores which are not symmetrically crustified. Replacements of homogeneous rocks may be banded also but not crustified. Valuable bodies of disseminated ores belong to this group; in these the rock is cut by many small fractures partly filled with ore minerals, and the rock between the fractures is impregnated or peppered with little dots of ore.

General Features.—The deposits formed at moderate depths by hot solutions are very numerous, and many of them are of great value. Many copper, zinc, lead, gold, and silver deposits in the American Cordillera belong to this group, which includes nearly all the more valuable copper deposits of Nevada, Colorado, Montana, Utah, Arizona, New Mexico, and other Western States, as well as many deposits in Mexico and British Columbia. Many of the deposits fill fissures and are for the most part tabular or rudely tabular; usually there has been extensive hydrothermal metamorphism of the wall rock along the fissures, and in a large number of deposits the wall rock is replaced by ore. The alteration of the wall rocks of these deposits is discussed on pages 237 to 251.

At moderate and shallow depths the depositing solutions are mainly liquid and the openings or systems of openings are in general connected freely with the surface. The solutions in the fissures move to places of less pressure, which in the main are upward. In some districts the depositing solutions were clearly ascending waters, and as the ores are closely associated geographically with igneous rocks and as the period of deposition nearly everywhere followed a period of igneous intrusion, the conclusion is inevitable that the waters were hot. Although the solutions are believed by many investigators to be in the main of magmatic origin, it is possible that some of the deposits may have been formed by hot circulating ground water of meteoric origin; others must have been deposited in fissures that received contributions of meteoric waters from above and magmatic water from below. The chilling effect of meteoric water, which at moderate depths would collect in the upper parts of the fissures, was doubtless a potent agent for rapidly reducing the temperature of the ascending metal-bearing solutions and thereby causing precipitation. The sources of waters that deposit metalliferous ores are discussed on page 274.

From studies of geologic structure many of the deposits are known to have been formed at depths of not much more than a mile below the surface at the time of deposition. Some of them—for example the Granite vein, at Philipsburg, Mont.—appear to have been formed as much as 7,000 feet below the surface. Others have probably formed less than a mile below the surface.

Occurrence.—The veins of this class are usually associated closely with igneous rocks; some of them are inclosed in walls of igneous rock; others are in sedimentary beds near igneous rocks (Fig. 26). The igneous rocks to which they are genetically related range from acidic to basic but are mostly either intermediate in composition (diorites, diorite porphyries) or grade toward the acidic end of the series (granites, alaskites, granodiorites, monzonites, quartz porphyries). A considerable number of these deposits, however, are genetically related to basic rocks—for example, the copper deposits of the Coronado vein at Morenci, Ariz., the silver ores at Cobalt, Ontario, and other deposits of gold and silver. As a rule the deposits are less than a mile away from igneous rocks, but a few are several miles from known outcrops.

The deposits of the deep zone are in the main genetically related to the granitoid rocks; the contact-metamorphic deposits are related to the granitoid rocks or the deep-seated porphyries;

the lode deposits formed at moderate depths are genetically related to the granitoid rocks, to deep-seated porphyries, or to porphyries formed very near the surface, but few or none of them have been formed in genetic connection with lava flows.

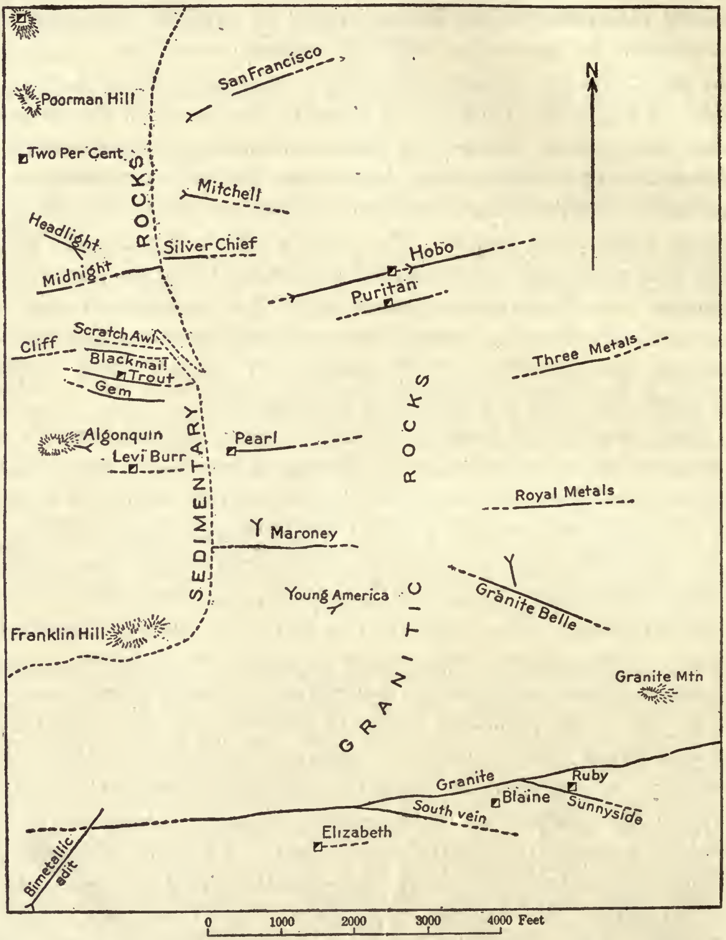

FIG. 26.—Sketch of area near Philipsburg, Montana, showing veins of the same system in both igneous and sedimentary rocks.

Pegmatite veins, contact-metamorphic deposits, and the more typical deposits of the deep vein zone (bearing heavy silicates, pyrrhotite, and magnetite) are generally formed in or near igneous rocks. Ore bodies formed at moderate depths by hot solutions, on the other hand, may be deposited at considerable distances from the magma. The openings near the surface are larger than those at greater depth, and the solutions circulate in them more freely. Nearly all such solutions are highly siliceous, and therefore, in accordance with well-known chemical laws, they do not so readily attack and replace quartzite or other highly siliceous noncalcareous rocks they may traverse. Consequently in such rocks they may carry the metals far from their sources. Where the siliceous solutions encounter limestones, however, there is usually rapid chemical interchange between the solutions and the wall rock, and deposition will generally take place relatively near the parent magma.

Composition.—The metals contained in this group of deposits include gold, copper, silver, lead, zinc, antimony, and arsenic. Small amounts of nickel, cobalt, bismuth, manganese, and other metals are recovered from some of them.

Minerals found in deposits formed at moderate depths by hot solutions are listed below. In this list some secondary sulphides are included. Besides these there are many minerals formed by decomposition in the oxidizing zone.

ankerite
apatite
argentite
arsenopyrite
barite
bauxite
bismuth
bismuthinite
bornite
calaverite
calcite
celestite
chalcocite
chalcopyrite
chert
chlorite
cinnabar
cobaltite
covellite
dolomite
enargite
fluorite
galena
gold
molybdenite
muscovite
niccolite
opal
orpiment
orthoclase
pentlandite
petzite
platinum
polybasite
proustite
pyrargyrite
pyrite
quartz
realgar
rhodochrosite
rhodonite
sericite
siderite
stephanite
stibnite
sylvanite
tellurides
tennantite
tetrahedrite
tungstates
zinc blende

A large group of minerals are formed in igneous rocks, in pegmatites, in contact-metamorphic deposits, during regional metamorphism, and in deep veins, but not normally in veins formed at moderate depths. Among them are amphiboles, diopside, garnet, graphite, hornblende, ilmenite, pyrrhotite (?), rutile, scapolite, specularite, spinel, topaz, and tourmaline. Magnetite, which is formed in these deposits under certain conditions of surface alteration, is rarely if ever a primary mineral in the deposits.

Shape.—Most of the deposits of this group are formed in and along easily recognized fissures; they are short in one and long in two dimensions. They may be vertical or flat or may dip at any angle. Several small, closely spaced fissures form a sheeted zone. Where metallization is localized by the intersection of two fissures, or a dike and a fissure, or a sedimentary bed and a fissure, the ore body is long in one and short in two dimensions. Such deposits are termed pipes or chimneys. Stockworks, ore folds, and bedding-plane deposits[1] are also included in this group.[1]

Size.—The deposits of this class range in size from ore bodies that have become exhausted in mining a few carloads to ore bodies containing millions of tons. Some of the fissures are filled only here and there, others are filled with material that is of too low grade to work, and still others contain workable bodies in a larger mass of low-grade material. Many deposits of this group are workable only where they have been enriched by superficial alteration, although a large number are rich in the primary concentration.

Texture.—In deposits formed at moderate depths in open fissures, the minerals, are very commonly arranged in rude sheets (Figs. 1–3), quartz and sulphides alternating, and the sheets are generally parallel to the walls of the fissures or to surfaces of fragments of rock in the veins. This structure, on the whole, is much more pronounced than in the veins formed at great depths. Where a vein is not completely filled the open space is lined with crystals pointing toward the center, and this position is in general characteristic of long crystals that form crusts. Banding has been noted in replacement deposits also, and locally it occurs even in rocks that were not banded before replacement, but it is relatively rare and is not crustified. Where symmetrical crustification or comb structure appears in ore that has replaced the country rock, it has probably been developed on a local fracture or in a solution cavity. A large number of replacement deposits and replacement veins belong to this group. They are discussed on pages 237 to 248. In many of the fissure fillings the banding is symmetrical—that is, the same series is shown from either wall to the center (see Fig. 27). More commonly, however, such symmetry is only faintly indicated or is entirely lacking. Veins formed at all depths may

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[1] Definitions given on pages 184–190.

be brecciated and cemented by crustified material belonging to a later period of deposition (Fig. 28).

The great disseminated copper ore bodies of Bingham, Utah; Ely, Nev.; Morenci, Ariz.; Santa Rita, N. Mex.; and other similar "copper porphyries" belong to this class. In these deposits many closely spaced, unsystematically arranged cracks are filled with iron and copper sulphides, and the rock between is dotted with small masses of the sulphides. The metals are somewhat regularly distributed, so that it is possible to work the entire low-grade mass at a profit if operations are conducted on a sufficiently large scale.

FIG. 27.—Section of banded vein, Pinos Altos district, New Mexico. (*After Paige, U. S. Geol. Survey.*)

Age.—Many of the deposits of this group were formed in comparatively late geologic time. Many of the epigenetic deposits associated with intrusive rocks that were formed in Tertiary time are included in this class. The deposits of this group are not confined to rocks invaded by Tertiary intrusives, however, but include also large ore bodies associated with igneous rocks which were intruded before the beginning of the Tertiary period. The group includes also some deposits formed in early Paleozoic and pre-Cambrian time. The classification is based on depth of formation rather than age: the deposits may have formed at any time, yet when the classes of deposits are compared, the relationship between age and certain fairly constant characteristics is apparent: the younger rocks were generally under light loads where the associated deposits now exposed were formed, but older rocks may have been more deeply buried at the time of their metallization.

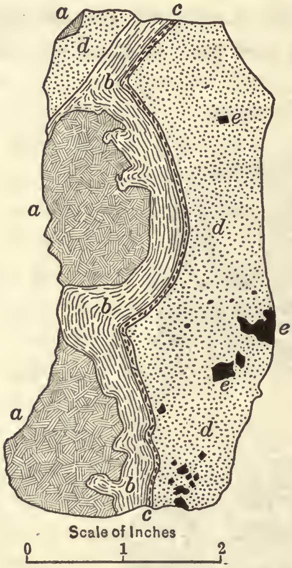

Fig. 28.—Sketch of specimen showing cementation of fragments of galena (*a*) belonging to the first period of deposition by a crustified material belonging to the second period and deposited in the following order: 1, Finely banded (crustified) brown carbonates (*b*); 2, a thin crust of quartz with sulphides (*c*); 3, mingled brown carbonates and fine quartz (*d*) containing some pyrite (*e*) and a little galena (*a*). (*After Spurr, Garrey, and Ball, U. S. Geol. Survey.*)

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CHAPTER VIII

DEPOSITS FORMED AT SHALLOW DEPTHS BY HOT SOLUTIONS

Occurrence.—In igneous and sedimentary rocks. Many are in or near intrusive rocks consolidated at shallow depths. Common in regions of late igneous activity, especially in or near Miocene and later intrusives; in rocks that have not been deeply eroded since the ores were deposited.

Composition.—Minerals include simple sulphides, such as pyrite, sphalerite, galena, chalcopyrite, stibnite, and cinnabar, with the tellurides, selenides, and complex antimony and arsenic sulphosalts. Fluorite, chalcedony, adularia, barite, and alunite are commonly present. The metals include gold, silver, quicksilver, antimony, arsenic, tungsten, lead, and zinc. Copper is a valuable constituent of zeolitic deposits but is rarely present in large quantities in sulphide ores formed at shallow depths.

Shape.—Many are simple tabular fissure veins. Ledges and irregular replacement deposits are developed in shattered rocks. Irregular veins with ore chambers are characteristic, but bedding-plane deposits and saddles are less common than among the deposits formed at moderate depths.

Size.—Some deposits are small; others are large. Bonanzas are frequently found in the low-grade ore.

Texture.—Comb structure and crustified banding are common; vugs are nearly always present; many deposits are formed by replacement. Although hydrothermal alteration of country rock is usually extensive, the ore is generally deposited in or relatively near the fractures. In many districts lamellar quartz is developed in cleavage cracks of calcite, and when the calcite is dissolved it releases a quartzose ore with peculiar interpenetrating blades.

General Features.—Deposits formed at shallow depths by hot solutions constitute one of the most valuable classes of ore deposits. They have produced a large part of the world's silver and considerable amounts of gold. The zeolitic copper lodes that are here included are among the most valuable sources of copper. Nearly all the quicksilver produced is obtained from deposits of this group, and also a little lead and zinc. These deposits naturally are not set off by sharp dividing lines from deposits formed at moderate depths, and there are numerous transitional types.

Occurrence.—The deposits are found in all kinds of igneous rocks—acidic and basic, granular and glassy—also in sedimentary rocks. Generally they are in or near masses of intruding rocks. In the American Cordillera they are associated at a great many places with intrusive porphyries and andesites. Most of those found in flows or in sedimentary beds are not far from intrusive masses. Structurally nearly all the deposits of sulphide ores are fissure fillings or formed by replacement along fissures. Bedding-plane sulphide deposits, though not unknown, are rare in this class.

The extensive zeolitic copper deposits of the Lake Superior region, which were formed in intergranular spaces in conglomerates, in vesicular cavities and small cracks in amygdaloids, and by replacement of both of these rocks, doubtless have a comparatively complex genesis, some features of which are as yet obscure; but if the successive metallized beds are regarded as having been filled or impregnated one after another, between the periods of flows and before tilting, they must be placed in this group, although structurally they are unlike the common types.

Composition.—The deposits formed at shallow depths by hot solutions have supplied considerable gold and enormous quantities of silver. In many places, as on the Comstock lode and at Tonopah and Tuscarora, Nev., both gold and silver are found in large amounts in the same deposit. There are some deposits, also (Cripple Creek, Colo.; Goldfield, Nev.), in which gold is found almost to the exclusion of silver, and a few in which silver only is important. In the sulphide ores copper is generally subordinate, although not a little is recovered as a by-product of gold and silver mining. The great bodies of copper sulphide ore, such as are typical of the group of deposits formed at moderate depths, are not represented in this class. Much copper, however, is obtained from zeolitic lodes.

Practically all the quicksilver deposits, the world over, belong to this group. Lead and zinc, though generally subordinate, are present in many of these deposits and are commonly recovered as by-products of concentrating or smelting the gold and silver ores.

Among the common constituents of these deposits adularia (vein-forming orthoclase) is abundant in many districts (Tonopah, Nev.; Cripple Creek and Creede, Colo.); alunite is its close associate at Goldfield, Nev., and in some other districts; and other sulphates are commonly developed. Carbonates are plentiful, especially calcite. Zeolites are abundant in the native copper ores of Michigan. The list below includes minerals of the deposits formed at shallow depths, as well as some secondary sulphides. Besides these, many minerals are formed during decomposition in the zone of oxidation.

adularia (valencianite)
alunite
analcite
ankerite
arsenopyrite
barite
bauxite
bismuthinite
bornite
calaverite
calcite
celestite
chalcedony
chalcopyrite
chert
chlorite
cinnabar
cobaltite
copper
dolomite
fluorite
galena
gold
kalgoorlite
kaolin
magnesite
marcasite
muscovite
molybdenite
opal
platinum
polybasite
proustite
pyrargyrite
pyrite
quartz
rhodochrosite
rhodonite
realgar
sericite
silver
stephanite
stibnite
stilbite
stromeyerite
sylvanite
thuringite
tungstates
tellurides
tennantite
tetrahedrite
zeolites
zinc blende

Some minerals that are stable up to moderate depths are not formed near the surface. The heavy silicates characteristic of deposits formed at great depths are lacking in this group. Pyroxene, amphiboles, tourmaline, topaz, garnet, biotite, magnetite, specularite, and pyrrhotite are practically nowhere present in lode ores formed at shallow depths, although some of these minerals are said to form as products of volcanic sublimation. Rhodochrosite and manganiferous calcite are very common, as are also complex silver-antimony sulphides and silver-arsenic sulphides. Mineral associations are discussed on pages 230 to 267.

Shape.—As the deposits of this group are generally related to fissures they do not differ greatly in shape from the deposits formed at moderate depths; tabular bodies or combinations of tabular bodies predominate. Bedding-plane deposits of sulphide ore, which are so commonly formed where limestones are attacked at moderate depths, are less abundant in this group, although they may be formed at shallow depths where the soluble beds are capped by shales or other impermeable rocks. Anticlinal deposits and "ore folds" are rare. Pronounced hydrothermal alteration of the wall rock is common and is as a rule attended by replacement of the wall rock with ore.

Size.—The deposits range in size from small veins and masses, such as some of the ore ledges of Goldfield, Nev., to enormous bodies of quartz and ore, such as make up the Comstock lode. Precipitating processes are especially active near the surface, and the metals may be thrown down in great masses that are relatively rich. Indeed, this class of deposits more than any other may be called the "bonanza group."

Texture.—The texture of these deposits is in the main like that of lodes formed at moderate depths. Vugs (Fig. 29) are perhaps more common. In many deposits chalcedony and quartz form bands of striking beauty. A structure common in calcite ores in several deposits in the Western States shows blades of calcite joining at angles similar to the cleavage angles of calcite. Such ores are found at De Lamar, Idaho (Fig. 30); Marysville, Mont.; Bullfrog and Manhattan, Nev.; and in other districts. The calcite, after it was formed, was filled by small veinlets of quartz occupying the cleavage planes and locally cutting across the crystals from one plane to another. After the lime carbonate is dissolved, the thin blades of silica remain as pseudomorphs of the calcite cleavage. Where the calcite is manganiferous many of the blades of silica are coated by sooty manganese oxide, locally carrying gold.

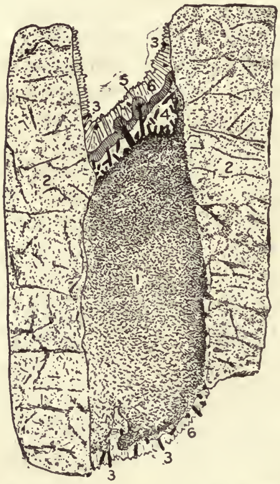

Fig. 29.—Local structure in C. K. & N. vein, Cripple Creek, Colo. Walls consist of reddish granite containing pyrite in cracks perpendicular to the vein. 1, Fragment of altered rock wedged in fissure; 2, minutely fissured granite with pyrite; 3, calaverite; 4, earlier generation of quartz; 5, radial pyrite; 6, later generation of quartz. (*After Lindgren and Ransome, U. S. Geol Survey.*)

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Fig. 30.—Ore from De Lamar mine, De Lamar, Idaho. The quartz blades filled cracks of calcite or barite, which subsequently was dissolved. (*After Lindgren, U. S. Geol. Survey.*)

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CHAPTER IX

DEPOSITS FORMED AT MODERATE AND SHALLOW DEPTHS BY COLD METEORIC SOLUTIONS

Occurrence.—Mainly in sedimentary rocks—limestones, shales, and sandstones. Organic matter or other reducing agents are commonly present in noteworthy amounts. Many of the ores occur in solution cavities and in zones of brecciation and subordinately in fissures and faults. Some are formed by replacement.

Composition.—The principal minerals are sulphides of zinc, lead, iron, and copper, with their alteration products and oxides of iron and manganese. Gangue minerals include calcite, chert, dolomite, jasper, barite. Mineral simplicity is characteristic. Heavy silicates are absent, and complex antimony, arsenic, selenium, and tellurium minerals are rarely if ever present. The metals include lead, zinc, copper, uranium, vanadium, iron, and manganese.

Shape.—Large tabular upright bodies like some of the fissure veins genetically related to igneous rocks are very rare, but "sheet ground" is developed in bedding planes, forming extensive tabular ore bodies. Crevices, gash veins, runs, or flats and pitches are characteristic in some districts. Many of the deposits are very irregular, especially those that fill solution cavities.

Size.—Some of the bedding-plane deposits, the disseminated lead deposits of southeastern Missouri, and deposits in "sheet ground" in the Joplin district, are very large. The larger bodies are parallel to bedding planes and in rocks not tilted are flat-lying. Many of the deposits are small.

Texture.—Solution cavities, crustified banding, and symmetrically lined vugs are common, but the regularly banded quartz veins so conspicuous among deposits genetically related to igneous rocks are rare. Brecciated structure is common. In some districts "disseminated ore" is developed, the metallic sulphides being sparingly but somewhat regularly distributed through great bodies of rock.

General Features.—The deposits formed at moderate and shallow depths by cold meteoric solutions include many valuable ore bodies, among them the lead and zinc deposits of the Mississippi Valley. Most of them are far from outcrops of igneous rock, and some are more than a hundred miles away. It appears improbable that buried igneous rocks, contemporaneous with or later than the formations that contain the ore are concealed below the surface, near enough to the zone of fracture for magmas to have contributed water or mineral salts to the areas containing these deposits, for the mineralized areas are large, and extensive igneous activity would probably be attended by the eruption of lavas at one place or another. It is also unlikely that intrusives many miles away have contributed the metals. In the West, where the larger ore deposits are almost invariably associated with igneous rocks, they are generally in or grouped closely around intrusives. Only exceptionally are they as far as one mile from outcrops of igneous rocks. Finally, in some of the many districts containing the deposits that are assumed to have been formed at moderate depths by cold solutions there is no evidence of tilting, extensive faulting, or other deformation such as ordinarily attends igneous activity.

As the solutions that formed these deposits were meteoric waters, not heated by igneous rocks, they were cold or at least not warmer than meteoric ground water would become by circulating through rocks that probably have the normal heat gradient for the earth, which is about 1°C. for 30 meters. As the waters were cold, the country rock has suffered no hydrothermal metamorphism, and those changes which it has undergone are characteristic of weathering or they are such as may be brought about by hydrometamorphism or changes that take place through the agency of ground water below the zone of oxidation.

The solutions that have not been affected by volcanism have not in the course of their circulation undergone any very abrupt change of temperature: the range of temperature through which they have passed is controlled by the depth to which they have descended. The investigations of Kemp, Finch, Lane, and Rickard have shown that ordinarily ground water does not actively circulate even at moderate depths, except in rocks that are especially permeable. At a depth of half a mile the normal heat increment would be less than 30°C. and the temperature not over 60°, and at 1 mile it would not be 100°C. On account of this narrow range of temperature, cooling can not have been so potent a cause of precipitation as in the classes of ore deposits formed by hot solutions, and probably it is almost negligible. The changes in pressure also are much less than those affecting magmatic waters.

The chief cause of precipitation is not decrease in temperature —indeed, it has been shown that some of the deposits of this class were formed by descending solutions, whose temperature would increase as they progressed downward. Precipitation is brought about by changes in chemical environment, rather than by great changes in temperature. The chemical changes result in forming new compounds of the metals—compounds that are less soluble than those which the solutions carried—by changes in the chemical character of the solutions, which react readily with the wall rock. Bituminous limestones and carbonaceous shales and sandstones are especially favorable for the development of deposits of this class. Recently Siebenthal[1] has discussed the chemistry of the formation of such deposits. In the Joplin region the metals may have been carried in solution as sulphates, chlorides, sulphides, zincates, carbonates, or bicarbonates. Precipitation may have been brought about by hydrogen sulphide, on the escape of carbon dioxide near the surface.

Occurrence.—The deposits of this group are found in both sedimentary and igneous rocks, but the best-known examples are in sedimentary rocks. The most valuable deposits of this class in the United States are the lead and zinc ores in limestone and associated chert in the Mississippi Valley. Some ores are found also in shale, but such ore bodies are small compared to those in limestone. Where shales and limestones are associated the ore is commonly deposited in the limestone near the shale. The shale, being less permeable, tends to impede circulation. If the solutions are rising the ores are likely to be deposited below a shale bed; if the solutions are descending they are likely to be deposited above the shale. In the lead and zinc region of southwestern Wisconsin most of the deposits are above the shale bed or "clay seam" in the Galena limestone, or just below the clay seam, where the rocks are fractured somewhat and solutions may pass through the fractures.

The deposits at Joplin, Mo., are on the southwest slope of the Ozark uplift, where a thick series of limestone and sandstone is capped by shale which dips southwest at low angles. In the Joplin region according to Siebenthal, the shale has been eroded from the top of the limestone. The solutions travel down the dip of the beds but are impounded by the shale and, being unable to move downward farther along the dip, rise through the limestone near the shale-limestone contact, where they deposit ores in the limestone (see Fig. 31).

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[1] SIEBENTHAL, C. E.: Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma. U. S. Geol. Survey *Bull.* 606, p. 42, 1915.

In the Southwest many copper deposits occur in sandstone and shale far removed from igneous rocks.[1] The principal ore minerals are chalcocite and bornite, which occur in a gangue of barite, calcite, and subordinate quartz. The copper sulphide in some deposits is precipitated on coal and other carbonaceous material (Fig. 32). The associated beds in many places contain sulphates and chlorides, and it is supposed that the copper was dissolved out of the rocks and concentrated in beds and along fissures, where precipitation was favored by the presence of organic matter.

The precipitation of the metals by organic matter is not the only way in which precipitation may be accomplished. Small amounts of lead and zinc sulphide may be dissolved by carbonic acid, the process yielding lead and zinc carbonates and hydrogen sulphide.[2] In depth in the presence of carbon dioxide the metallic sulphides are not precipitated, but when the solutions rise again near to the surface carbon dioxide escapes, and the metals are deposited as sulphides.

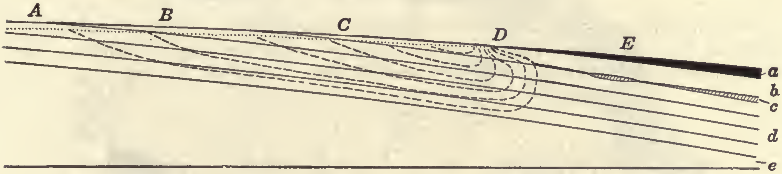

Fig. 31.—Diagram showing stage in artesian circulation, Joplin region, Mo. *A–E*, Stages in erosion of Pennsylvania shale. *a*, Pennsylvania shale; *b*, Mississippian limestone; *c*, Chattanooga (Devonian) shale; *d*, Ordovician and Cambrian rocks; *e*, pre-Cambrian rocks. (*After Siebenthal, U. S. Geol. Survey.*)

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[1] Emmons, S. F.: Copper in the Red Beds of the Colorado Plateau Region. U. S. Geol. Survey *Bull.* 260, pp. 221–232, 1905.

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[2] Siebenthal, C. E.: *Op. cit.*, p. 52.

Uranium and vanadium are found in the Southwest in deposits in sandstone far removed from igneous rocks. The metals are believed to have been present in small amounts in the sandstone, from which they were dissolved by ground water. They were precipitated at favorable places, especially in the presence of organic material, such as decayed trees and reeds.

Fig. 32.—Section of chalcocite (light) replacing coal (dark) Nacimiento district, New Mexico. Upper part of specimen is altered by oxidation. (*Redrawn from plate by Lindgren, Graton, and Gordon, U. S. Geol. Survey.*)

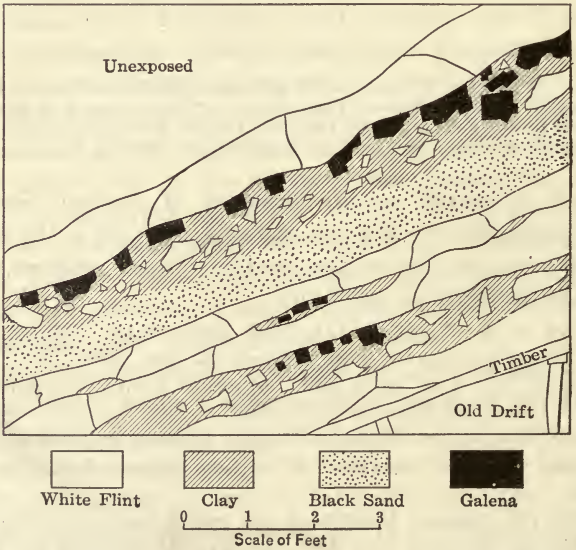

Fig. 33.—Ore in the Ruby Trust mine, Granby, Joplin region, Missouri. (*After Buckley and Buehler.*)

In some deposits calcite cement in sandstone appears to have precipitated the metals.

Iron dissolved from country rock in sulphate or carbonate solutions may be precipitated as oxide by descending waters. At many places, small veins are deposited in fissures or replace the rock along fissures. Manganese, under some conditions at least, is dissolved more readily than iron. It is easily precipitated as oxide when acid solutions are neutralized by alkaline rocks. Many manganese deposits have been formed by precipitation from cold solutions.

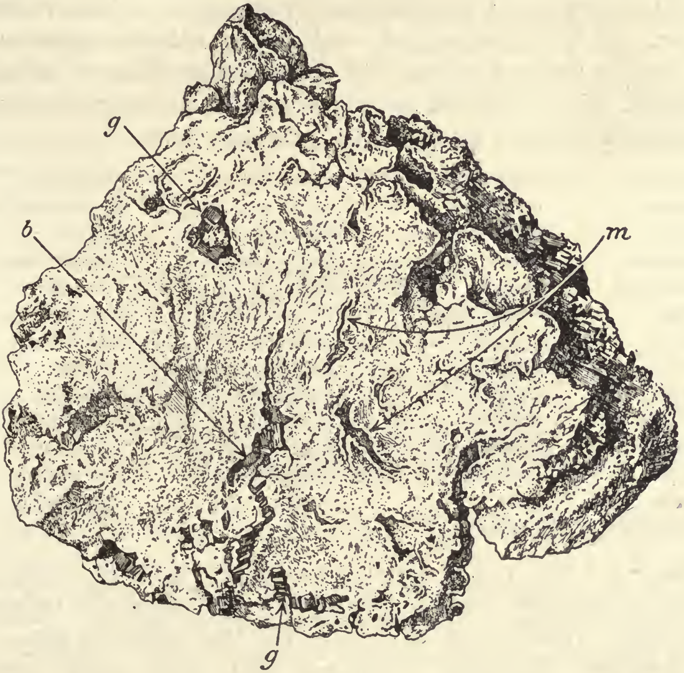

Fig. 34.—Honeycomb ore from the Hazel Green mine, Hazel Green, Wisconsin. *m*, Marcasite; *b*, zinc blende; *g*, galena. (*After Bain, U. S. Geol Survey.*)

Composition.—Deposits formed at moderate and shallow depths by cold solutions yield a large part of the world's supply of lead and zinc and some copper but little or no gold or quicksilver, and only a little silver. The ores generally are of simple composition (Figs. 33 and 34). As pointed out by Bain,[1]

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[1] Bain, H. F.: Some Relations of Paleogeography to Ore Deposition in the Mississippi Valley. Internat. Geol. Cong., Mexico, 1907. The Fluorspar Deposits of Southern Illinois. U. S. Geol. Survey *Bull.* 255, pp. 61–67, 1905.

the complex arsenic and antimony minerals are generally absent in these deposits. Some of the galena, however, carries antimony,[1] and in some regions as much as 1 per cent. is present. Minute quantities of silver may also occur in galena. The uranium and vanadium deposits of southwestern Colorado are included in this class. Deposits of iron oxides and of manganese oxides are formed by precipitation in shattered zones of limestone and of other rocks.

The minerals that are found in deposits of this class are listed below. Of these, many are confined to oxidized zones near the surface and are regarded as alteration products of primary minerals. In this group of deposits it is not always easy to distinguish between primary and secondary ores.

alum
anglesite
ankerite
aragonite
aurichalcite
azurite
barite
bauxite
bornite
calamine
calcite
celestite
cerusite
chalcanthite
chalcedony
chalcocite
chalcopyrite
chert
chlorite
chrysocolla
copper
covellite
cuprite
fluorite
galena
goethite
gold
goslarite
greenockite
gypsum
hematite
hydrozincite
kaolin
limonite
malachite
manganite
marcasite
millerite
opal
psilomelane
pyrite
pyrolusite
pyromorphite
quartz
rhodochrosite
selenite
siderite
smithsonite
sulphur
uranium compounds
vanadium compounds
zinc blende

Shape.—Large rudely tabular bodies are common in the deposits of this class, but as noted above they generally lie along the beds. Great veins cutting across the beds are rare. In southwestern Wisconsin "crevices" and "gash veins" occur, but these are thinner and less persistent than normal veins. In that region flats and pitches are formed where beds rich in volatile hydrocarbons have shrunk and let down limestone beds above them, causing the limestone to fracture along horizontal and steeply dipping planes (see Fig. 35).

In the Joplin region some of the deposits have formed in ancient caves, in limestone sinks, and in openings between fragments that have formed superficial chert breccias that were subsequently covered by later beds. Such deposits are very irregular in shape. Those that have formed in solution cavities are likely to be long

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[1] SIEBENTHAL, C. E.: *Op. cit.*, p. 216.

in one and relatively short in two dimensions. Deposits in which solutions have replaced organic matter vary widely in shape, which depends on the distribution of the material that caused precipitation and on the extent of replacement.

Size.—The large tabular upright ore bodies that are commonly referred to as "true fissure veins" are conspicuous in many districts where the ores are genetically related to igneous rocks but are rare in regions where the deposits were formed by cold meteoric waters. Extensive bedding-plane deposits are formed in such regions; the Joplin district of southwestern Missouri and the lead district of southeastern Missouri contain bedding-plane deposits that are as large as the great veins above mentioned. Where deposits have been formed in ancient underground water channels they may be followed here and there over distances of several miles. A great many deposits of this group, however, are small. Among the hundreds of deposits of copper, uranium, and vanadium that replace organic matter in the Southwest, few large ore bodies have been developed. While many primary iron and manganese deposits are formed by deposition from cold solutions, most of them are small. On the other hand, some of the largest iron-ore deposits have been formed by enrichment of low-grade protores in weathering.

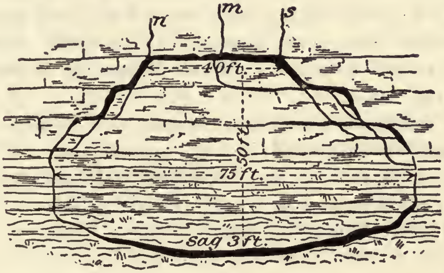

FIG. 35.—Section of flats and pitches of Roberts mine, Linden, Wisconsin. *n*, *m*, *s*, North, middle, and south crevices. (*After T. C. Chamberlin.*)

Texture.—The texture of the deposits in this group differs but little in kind from that of deposits formed by hydrothermal processes. In both classes crustified banding and symmetrically lined vugs are common. Delicately banded quartz, which is so common in deposits formed by hot waters, is rare in ores formed by cold solutions. In the deposits of southwestern Wisconsin crustified bands of calcite around brecciated fragments are common. Nodular and tabular masses are formed in which the order of deposition is marcasite, sphalerite, galena. The great bulk of the ore of this class, however, shows little crustification. In the Joplin region much of the ore has a brecciated structure, consisting of chert fragments cemented with sphalerite. In the lead district of southeastern Missouri most of the ore is disseminated in beds of carbonaceous limestone. Nodular bodies and geodes are of common occurrence in deposits of iron and manganese oxides.

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CHAPTER X

SEDIMENTARY DEPOSITS

Occurrence.—In sedimentary rocks—gravels, sands, clays, conglomerates, sandstones, limestones, shales, etc.—usually as beds or parts of beds, or disseminated through certain beds. All are oriented with the contemporaneous strata. Where they have not been disturbed they are flat-lying.

Composition.—In the clastic sedimentary deposits the minerals are the residual or stable minerals of older rocks and older deposits. They include gold, platinum, iron, tin, rutile. zircon, rare-earth minerals, gems, and other relatively insoluble materials. In beds which are chemical precipitates iron and manganese are the most important metals. Nonmetallic substances are coal, phosphate rock, salines, gypsum, clays, and many other materials.

Shape.—In general two dimensions are great and one is relatively small. Some placers are long in one and short in two dimensions. Equidimensional deposits are rare but not unknown.

Size.—Some are small; others are very extensive.

Texture.—Some deposits of this class have a structure characteristic of sedimentary rocks, such as is produced by sorting in water—bedding, cross-bedding, etc. In some the constituent particles are rounded by wear. Some contain fossil remains. Included anisodiametric bodies deposited mechanically with the beds are generally oriented with their short dimensions across the beds. The chemical sediments may be oolitic, crystalline, or amorphous. Banded structure is common but is rarely symmetrical and is not crustified. Comb structure and vugs lined symmetrically with banded crusts are never present except where infiltration has taken place since the deposits were formed.

General Features.—Weathering and erosion are processes of mineral segregation. A quartz diorite which has about the composition of the average igneous rock is composed of potash and lime-soda feldspars, quartz, muscovite, biotite, magnetite, augite, and other ferromagnesian minerals, and some minor constituents, such as titanite, apatite and pyrite. Normal weathering will tend to convert the rock to kaolin, quartz, and limonite; wad and bauxite also may form. With these "end products" of weathering titanite and some apatite will remain. Ground water, which generally contains carbon dioxide, will dissolve and carry away alkalies and alkaline earths as carbonates or bicarbonates; the sulphur is converted to sulphates. Some iron, aluminum, and silica also are dissolved, but more slowly than the alkalies and alkaline earths. Phosphorus and titanium dissolve very slowly. The dissolved materials will be carried to the sea and form organic deposits and chemical precipitates. Thus are supplied materials for beds of limestone, dolomite, chert, iron-bearing sediments, gypsum, phosphate rock, etc. The waters also carry in suspension or roll along their courses quartz, kaolin, limonite, and any heavy residual materials that may be present.

If the rocks decomposed contain deposits of metals, such as copper, zinc, tin, and platinum, the soluble metals like copper and zinc may be carried downward and reprecipitated, or they may be carried to the sea and subsequently precipitated there. The heavy, insoluble minerals, if any happen to be present, especially those which resist surface decomposition, like platinum, gold, and tin oxide, will generally be left behind in the beds of the streams not far from their outcrops.

Every constituent of the quartz diorite has a certain economic value if sufficiently concentrated, and when conditions are favorable many products may result from the processes of weathering, transportation, and deposition. But erosion seldom permits complete weathering, and the material, which is generally disintegrated mechanically before it is thoroughly decomposed chemically, passes to the sea in various stages of segregation. Thus the products of decomposition are generally found in various stages of impurity.

Sedimentary deposits are valuable sources of the metals. From them are obtained more than half of the world's iron, tin, and platinum, and much of the gold and manganese, as well as gems, many other nonmetallic products, and hydrocarbons. Although sulphides are present in many sedimentary beds,[1] sulphide ores of workable grade are comparatively rare among sedimentary deposits.

Sedimentary deposits may be divided into those concentrated mechanically and those concentrated chemically. Deposits concentrated mechanically include basal conglomerates of iron ore, and the placers of platinum, gold, tin, etc. These

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[1] Andrussow, N.: Le mer noire. VII Congrés Géol. Internat. *Guide des excursions*, Excursion XXIX, 1897.

Doss, Bruno: Melnikowit, ein neues Eisenbisulphid, und seine Bedeutung für die Genesis der Kieslagerstätten. *Zeitschr. prakt. Geologie*, Jahrg. 20, pp. 453–483, 1912.

deposits are marine, lacustrine, or fluviatile, the classification depending on the nature of the body of water in which they have found rest. Deposits may be concentrated chemically as a result of evaporation, reduction, or oxidation, or by organic agencies. Examples of these are salt beds, coal, gypsum, and some iron ores.

Many deposits of sedimentary origin are workable in their primary state. Others supply the protores, which are further concentrated by weathering into workable ore bodies.

Occurrence.—Deposits of sedimentary origin may be found in association with all kinds of sedimentary rocks. Deposits of mechanical origin are likely to be in conglomerates, sandstones and shales; deposits of chemical origin are commonly in or associated with limestones, shales, or fine-grained sandstones.

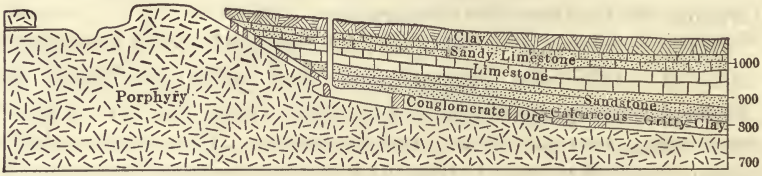

FIG. 36.—Section showing iron-ore deposits of Iron Mountain, Missouri. The iron has been quarried from openings at the top of the hill and mined underground at the base of the sedimentary series, where it formed a basal conglomerate. (*After Crane, Mo. Geol. Survey.*)

All the deposits of this class are syngenetic, or "contemporaneous" with rocks of the series containing them, but they are younger than the rocks stratigraphically below and older than the rocks stratigraphically above them. The ore-bearing beds may be much younger than the underlying rocks (see Fig. 36) or much older than the overlying rocks where they are separated from those rocks by unconformities. On the other hand, the deposits may form a continuous series with the underlying and overlying rocks. The mechanical sediments especially conglomerates are commonly unconformable with the underlying rocks and therefore may be considerably younger; the chemical sediments are more generally contemporaneous—that is, they form part of a series of beds that were deposited continuously, without interruptions due to great diastrophic movements and erosion.

Deposits of sedimentary origin may rest upon igneous flows, or intrusive rocks; above them there may be flows, sills, or sheets of igneous rock.

Some sedimentary deposits are superficial—that is, they are not covered by later formations. Examples are bog-iron deposits, some beds of salt, borax, nitrates, and surface placers. Other deposits of this class, after they are formed, are buried below later sediments or igneous flows.

Whether chemical or mechanical, all sedimentary deposits have been subjected to all the folding, faulting, or other deformation which has affected the associated beds and overlying formations (see Fig. 37). They are flat-lying only where they have not been disturbed by subsequent earth movements.

Composition.—The principal metals of sedimentary deposits include iron, manganese, gold, platinum, and tin. The rare-earth minerals monazite and xenotime should be mentioned also. A list of the minerals in sedimentary deposits would include essentially all minerals, for sedimentary beds are made up of materials from geologic bodies of all classes, mechanically disintegrated and weathered in varying degrees; but because some minerals resist weathering more than others, they are more common and relatively more abundant in mechanical sediments than the less stable minerals.

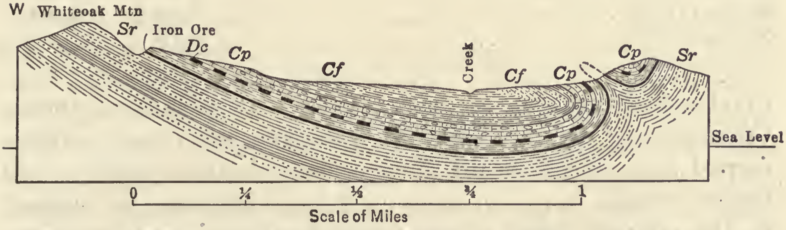

Fig. 37.—Section across Whiteoak Mountain syncline, Chattanooga, Tennessee, showing "Rockwood" or Trenton iron-ore bed. *Sr*, "Rockwood" formation; *Dc*, Chattanooga shale; *Cp*, Fort Payne chert; *Cf*, Floyd shale. (*After Burchard, U. S. Geol. Survey.*)

Certain minerals that are stable under conditions of weathering are listed below.

All the minerals listed below are dissolved very slowly in ground water. Most of them are hard and therefore not readily disintegrated mechanically. Gold and platinum, though soft, are malleable and therefore withstand abrasion. Limonite, kaolin, psilomelane, pyrolusite, and bauxite although resistant

MINERALS STABLE UNDER WEATHERING CONDITIONS

	Specific gravity	Hardness
Quartz (SiO_2)	2.65	7.0
Garnet (composition variable)	3.15–4.30	6.5–7.5
Kaolin ($H_4Al_2Si_2O_9$)	2.60	2.0–2.5
Bauxite ($Al_2O_3.3H_2O$)	2.30–2.40	2.5–3.5
Limonite ($2Fe_2O_3.3H_2O$)	3.60–4.00	5.0–5.5
Psilomelane (H_4MnO_5)	3.70–4.70	5.0–6.0
Pyrolusite (MnO_2)	4.73–4.86	2.0–2.5
Magnetite (Fe_3O_4)	5.17	5.5–6.5
Chromite ($FeCr_2O_4$)	4.32–4.57	5.5
Hematite (Fe_2O_3)	4.90–5.30	5.5–6.5
Platinum (Pt)	21.00	4.0–4.5
Gold (Au)	19.00	2.5–3.0
Cassiterite (SnO_2)	6.80–7.10	6.0–7.0
Monazite ([Ce, La, Di] PO_4)	4.90–5.30	5.0–5.5
Rutile (TiO_2)	4.20	5.0–6.5
Zircon (Zr SiO_4)	4.70	7.5

to chemical changes, are not resistant to mechanical forces. Consequently they are likely to be broken into small particles, carried away mechanically from coarser clastic sediments, and finally brought to rest in more quiet surroundings. In addition to the minerals listed above, goethite, gibbsite, wad, xenotime, and ilmenite should be mentioned.

Kaolin, quartz, iron aluminum and manganese oxides, and garnet are abundant in nature; the other minerals listed above are comparatively rare. The common minerals are in general not so resistant to disintegration as the rare ones. Muscovite, biotite, and apatite also resist disintegration but are less stable than the minerals named above. They are common, nevertheless, in mechanical sediments.

Metalliferous minerals found in the chemical sediments are siderite, limonite, goethite, pyrite, hematite, glauconite, chamosite, greenalite, manganite, wad, and psilomelane. Gangue minerals that are associated with these are chert, quartz, calcite, dolomite, and a number of other minerals, as a rule very finely comminuted. Of these kaolin and quartz are generally the most abundant. Nonmetalliferous minerals in chemical sediments include salt, gypsum, anhydrite, calcium phosphate, borates, nitrates, etc.

One group of sedimentary deposits that exhibits some puzzling features should be mentioned here. These are the marine oolitic and fossiliferous iron ores of the so-called Clinton type. They carry hematite, calcite, siderite, and quartz. The iron oxide occurs as fossils of shells of calcium-secreting organisms and doubtless has replaced lime carbonate. But because these shells are uniformly replaced over wide areas and are now distributed throughout beds that extend down the dip to great depths, far below the level of active oxidation, it is believed that the replacement of lime by iron occurred before the shells were deeply buried and the rock consolidated, probably soon after the shells sank to the bottom of the sea. Thus these deposits, though formed by replacement, are considered sedimentary and syngenetic, just as dolomites in which magnesia has replaced lime, probably under nearly similar conditions, are classed as sedimentary beds.

Shape.—Many sedimentary deposits, especially the chemical and organic deposits, approach the tabular form more closely than deposits of other classes. But broadly considered they are lenses, for they must pinch out somewhere, however extensive they may be. In general the thickness is comparatively uniform, at least more nearly uniform than in deposits of other classes. Many placer deposits formed along streams are long in one and short in two dimensions. Those formed on relatively swift streams are likely to be irregular, and their productive parts may lie in pockets.

Size.—Many of the deposits of sedimentary origin are very extensive. The iron-bearing formation of the Mesabi range, Minnesota, is traced over 100 miles; the Penokee-Gogebic iron range, in Michigan and Wisconsin, extends about 80 miles; and the Clinton iron-bearing formation, which contains overlapping lenses of iron ore, extends over areas of many hundreds of square miles. Beds of coal, gypsum, or rock phosphate may extend over thousands of square miles—indeed, the most extensive mineral deposits of economic value belong to this class. On the other hand, some deposits of sedimentary origin are very small. Some beds of bog iron and of bog manganese cover only a few acres, and some highly profitable placer deposits of this class are of small extent. Certain very extensive beds of iron ore less than 2 feet thick have been worked. Some of the sedimentary ore beds have great thickness; the Biwabik formation, which is the protore of the Mesabi iron deposits, is hundreds of feet thick.

Texture.—Many sedimentary ores are banded (Fig. 38). The mechanical sediments may show bedding, cross-bedding, and other evidences of sorting by water. Their constituent particles are commonly corroded or rounded by abrasion. Fossil remains of animals or plants may be present; in clastic sediments the fossils are generally broken. As the deposits are formed in water, bodies that are anisodiametric (not spherical) will lie with their longer axes approximately horizontal (Fig. 39); if the beds are subsequently tilted, these bodies will still lie approximately parallel to the bedding planes. If heavy minerals are present they tend to be concentrated at the bottom of the bed. Chemical sediments also are commonly banded.

Fig. 38.—Banded ore of sedimentary origin, Kennedy mine, Cuyuna range, Minnesota. Chert (light) alternating with hematite (black). (About natural size.)

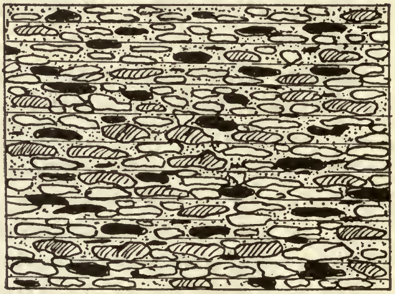

Fig. 39.—Section of sedimentary deposit. Anisodiametric bodies lie with their longer axes parallel to the bedding planes.

Although many sedimentary deposits are banded or bedded, they are unlike deposits that fill fissures in that the banding is nowhere symmetrically crustified (see page 3). The openings in these deposits are intergranular spaces or solution cavities. Vugs, which are common in veins, are lacking in sedimentary deposits and the open spaces are not lined by layers or crusts, one on the other, like cavities of veins. The deposits do not cross the bedding, and there are no contemporaneous veinlets extending from the main lodes into the country rock, such as those that extend from veins. Many sedimentary deposits have rather sharp contacts with the associated beds, whereas replacement deposits more commonly grade into and finger out in the wall rock. Many sedimentary deposits—for example, some sedimentary iron ores—are made up of thin, closely spaced bands of ore and barren country rock.

In some districts epigenetic deposits replace certain beds partly or almost completely. These deposits exhibit the broader structural relations of sedimentary beds, but certain details of structure serve to distinguish them. Such deposits are discussed on page 197. The relative abundance of various classes of deposits of certain metals is indicated by Fig. 40.

Fig. 40.—Diagram showing approximately the relative abundance of various classes of primary ores and protores of several metals. Broken lines indicate that classes of deposits are of little or no value. Broken lines with long dashes indicate rare deposits or deposits of subordinate value. Solid lines indicate valuable deposits—the value of the class being shown approximately by width of the line.

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CHAPTER XI

PRIMARY ORE SHOOTS

Many metalliferous deposits contain bodies of workable ore that are surrounded by lower-grade unworkable material. The term "ore shoot"[1] in the stricter sense is applied to these richer portions. More loosely, the term is applied to any body of valuable ore lying in the gangue or country rock. A body very rich and of good size is called a "bonanza;" a thin and rudely tabular body of richer ore is called a "pay streak;" and a smaller body not very large in any dimension is a "bunch" or "pocket."

As ore shoots are the most valuable portions of metalliferous deposits they are naturally of great interest to the miner. Their mode of occurrence and genesis may become apparent only after a comprehensive study of the structural and historical geology of a region containing them, the relations of the deposits to the structure, and the paragenesis of the vein matter.

A great many mineral deposits—by far the greater number of those so far discovered—are exposed at the surface. Their outcrops may be rich in valuable metals or they may be leached by surface waters, but their leached portions are characteristic and may be recognized by prospectors who have observed elsewhere

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[1] Penrose, R. A. F., Jr.: Some Causes of Ore Shoots. *Econ. Geol.*, vol. 5, pp. 97–133, 1910.

Van Hise, C. R.: Some Principles Controlling the Deposition of Ore. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 27–177, 1900.

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similar barren outcrops that pass into valuable deposits beneath the surface. Profitable deposits as a rule are explored as they are mined. "Ore against ore" is an old Cornish dictum. It is good prospecting to follow the ore body as far as practicable and to explore adjoining territory for similar deposits. The ore body is followed to its ends on drifts, raises, or winzes. These workings are generally pressed ahead beyond the workable deposit or ore shoot. Valueless vein matter near a deposit is prospected because there is generally a fair chance of finding ore in association with it.

A "blind" deposit is one that does not crop out. The country rock on all sides of a valuable deposit is regarded as favorable ground for prospecting unless the structural relations are unfavorable. Thus blind deposits may be discovered near those that are exposed.

Ore shoots may be of primary or secondary origin. A great many of them are formed by superficial alteration and enrichment; these are discussed on pages 124 to 169. Many, however, have been formed by primary processes at the same time as the deposits containing them. Primary ore shoots are discussed in the chapters treating the several classes of primary ores, the openings in rocks, and the structural features of epigenetic deposits. In this chapter some of the causes commonly controlling their formation are reviewed.

If magmatic segregation is brought about by gravity, the heavier metals should sink as they do in bullion or matte in an ore furnace. At Sudbury, Ontario, the nickeliferous pyrrhotite is at the bottom of the Sudbury laccolith, particularly in embayments in the underlying rock (page 12) and in dikes that make off from the bottom of the laccolith. If segregation takes place at considerable depth, however, the metalliferous matter may be injected into fissures like ordinary dikes. The entire dike may be the deposit, as at Iron Mountain, Wyo., where a dike of titaniferous iron ore over a mile long and 40 to 300 feet wide has been thrust into anorthosite.[1] In places magmatic segregation forms bands or layers of ore alternating with bands or layers of valueless minerals. The origin of these deposits is not clear. Much remains to be done before the problems of distribution of ore shoots segregated in igneous rocks are all solved.

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[1] Ball, S. H.: Titaniferous Iron Ore of Iron Mountain, Wyo. U. S. Geol. Survey *Bull.* 315, pp. 206–214, 1907.

In many pegmatites the little pockets or "nests" that contain gems or other valuable minerals are distributed with extreme irregularity. In some pegmatite veins, however, they are arranged rudely in zones, as at the Mount Mica mine, Paris, Maine[1] (page 22). Pipe-like bodies of pegmatite are not uncommon. Butler[2] has described a tree-like pegmatitic body of quartz in the San Francisco region, Utah, in which ore shoots are located on the branch-like extensions from the central body.

Contact-metamorphic zones are zones only in the broad sense. The rocks replaced are not all equally hospitable to ore deposition; some are more easily replaced than others, and in these the replacement is likely to extend farther from the intruding mass. Beds of pure limestone are generally more extensively replaced than impure limestones, shales, and sandy rocks. Not only are the zones of metamorphism erratic in their outlines, but the bodies of metalliferous ores within such zones are in general irregularly distributed. In some districts they are found by prospecting a geologic formation at a horizon that experience has shown is favorable for their development. Contact-metamorphic deposits are likely to be developed most abundantly in regions where igneous intrusives are closely spaced and in connection with intrusives of certain types (see pages 29 to 47).

Ore veins and similar deposits, whether they were formed in the deep vein zone, at moderate depths, or near the surface, are generally not uniformly mineralized but vary greatly in size and richness. Those formed at moderate depth and those formed near the surface more commonly contain rich primary ore shoots and bonanzas than those formed at greater depth, although rich primary deposits may be formed also in the deep vein zone. Certain depths of formation are more favorable than other depths. The maximum deposition often takes place also where the more open channels are provided and where they are most favorably situated. These channels may be intergranular spaces in sedimentary rock or openings along bedding planes. The richer deposits are sometimes found where the rocks were most highly shattered when the ore solutions penetrated them. Thus shear zones, sheeted zones, or areas of maximum fracturing and

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[1] Bastin, E. S.: Geology of the Pegmatites and Associated Rocks of Maine. U. S. Geol. Survey *Bull.* 445, p. 84, 1911.

[2] Butler, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent districts, Utah. U. S. Geol. Survey *Prof. Paper* 80, p. 125, 1913.

brecciation commonly control deposition. The planes of maximum fracturing may be along faults, at crests of folds, on conjugated fissures, or along certain brittle beds or dikes. Intersections of fissures may influence deposition favorably. Where the fissures meet at a small angle the rocks near the line of junction are likely to form thin wedges that are highly shattered and more easily replaced.[1] The mingling of solutions brought together at the junction of two crossing fissures may promote deposition.[2] Suitable channels may be provided also when dikes or any other brittle bodies are crossed by fissures, and their intersections may become sites of greater mineralization than other parts of fissures. One country rock may be more favorable to deposition than another on account of its chemical composition or because it is more easily fractured. If a fissure carries ore where it cuts a certain dike or bed, ore bodies should be sought for at its inter-section with similar dikes or beds and also where these dykes or beds are crossed by other fissures. Some long, slender ore bodies appear to have been formed along channels where ascending waters or gases rose to the surface through permeable rocks, to issue as hot springs. The remarkable ore shoot at the Anna Lee mine,[3] Cripple Creek, Colo., is a long, nearly vertical body of ore about 15 to 25 feet

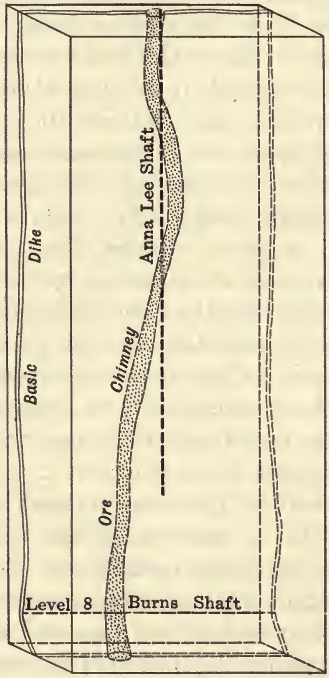

FIG. 41.—Stereogram of Anna Lee ore chimney, Cripple Creek, Colorado. (*After V. G. Hills.*)

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[1] PENROSE, R. A. F., JR.: Some Causes of Ore Shoots. *Econ. Geol.*, vol. 5, p. 110, 1910.

[2] VAN HISE, C. R.: Some Principles Controlling the Deposition of Ores. Am. Inst. Min. Eng. *Trans.*, vol. 30, p. 85, 1900.

[3] GROSS, WHITMAN, and PENROSE, R. A. F., JR.: Geology and Mining Industries of the Cripple Creek District, Colorado. U. S. Geol. Survey, *Sixteenth Ann. Rept.*, part, 2, p. 205, 1895.

LINDGREN, WALDEMAR and RANSOME, F. L.: Geology and Gold Deposits of Cripple Creek, Colorado. U. S. Geol. Survey *Prof. Paper* 54, p. 448, 1906.

in diameter, which follows a nearly vertical basic dike that is locally brecciated (see Fig. 41). It has probably formed where one or more fissures cross the dike. At the Bassick mine, Colorado,[1] a nearly vertical ore shoot over 800 feet long occurs in an agglomerate that has filled the neck of an old volcano. The ore deposit, according to S. F. Emmons, is connected genetically with decadent volcanic activity.

Some rocks, because they are impervious or not readily fractured, obstruct mineralizing solutions and promote deposition near their contacts. Thus at Rico, Colo.,[2] and at the Bremen mine, New Mexico,[3] ore shoots are formed in limestone at the contact with impervious shale. The impermeable gouge in some of the northwest veins at Butte, Mont.,[4] has locally dammed back the solutions and prevented continuous mineralization.

In some veins the ore shoots are nearly parallel to the dips of the veins; in others they plunge to one side or the other. There is no universal rule, although in some districts the larger number of ore shoots plunge in the same direction.

Deposits formed at moderate and shallow depths by cold solutions may contain either primary or secondary ore shoots. Some of these deposits show a close relationship to the structure of the region. In the Joplin district[5] the more valuable deposits are in limestone near the border of overlying shale, which is believed to have diverted the circulation of the ore solutions, causing them to rise to the surface. Some of the larger deposits are in ancient caves that were formed in Mississippian rocks before the Pennsylvanian rocks were deposited on them; others are in brecciated zones and basal breccia beds. In the Wisconsin region conditions for deposition were favorable in shallow basins or synclines, where shrinkage of an oil shale provided openings

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[1] Emmons, S. F.: Geology of Silver Cliff and the Rosita Hills, Colorado. U. S. Geol. Survey *Seventeenth Ann. Rept.*, part 2, p. 435, 1896.

[2] Rickard, T. A.: The Enterprise Mine, Rico, Colorado. Am. Inst. Min. Eng. *Trans.*, vol. 26, pp. 906–980, 1896.

Ransome, F. L.: The Ore Deposits of the Rico Mountains, Colorado. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 2, pp. 291–312, 1901.

[3] Penrose, R. A. F., Jr.: Some Causes of Ore Shoots. *Econ. Geol.*, vol. 5, p. 117, 1910.

[4] Sales, R. H.: The Localization of Values in Ore Bodies and the Occurrence of Shoots in Metalliferous Deposits. *Econ. Geol.*, vol. 3, p. 330, 1908.

[5] Siebenthal, C. E.: Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma. U. S. Geol. Survey *Bull.* 606, p. 26, 1915.

for deposition and also a precipitating agent.[1] The occurrence of deposits formed by precipitation in and around organic matter depends on the distribution of such matter, which in turn depends on the conditions of sedimentation at the time the rocks inclosing the deposits were formed.

Sedimentary deposits are not uniformly metalliferous. In placer deposits there may be richer sands or gravels at the bottom of the bed, just above the bedrock or above a stiff clay seam. By scour and fill the waters of the stream stir up the gravel, allowing the heavier part to sink as it does in a miner's pan. Generally not all the river bed carries gold. As a rule the gold is accumulated in streaks and in largest amounts in places where the stream's velocity is checked. On a meandering stream the placers are likely to accumulate on the inner sides of the bends.

Basal conglomerates of iron ore (page 86) may be classed as ore shoots; generally they occur in beds that lie unconformably above iron-bearing formations.

In many sedimentary series the beds vary greatly in composition. Beds of nearly pure iron oxide or iron carbonate may alternate with chert. The individual beds range in width from less than ¼ inch to many feet. Such variations are common and are attributed to changes in the conditions of sedimentation. These conditions are varied and complex, and their causes are in large part obscure. Structural studies may show where the valuable beds are, but it is generally impossible to predict their changes in advance of exploration. Ores of aluminum, manganese, and other metals may be segregated in beds or parts of beds.

From this brief discussion of examples of primary ore shoots it is evident that the occurrence of such shoots depends on a great variety of conditions and causes. The controlling factors in one district may not control in another. Each district should be studied as a separate problem, and the laws that govern ore deposition within it should be established independently. By mapping the geology the structure is made clear, and then the structural relations of the ore bodies are apparent. Although the geologist may not accurately predict in advance of exploration where the richer primary ore bodies may be found,

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[1] GRANT, U. S.: Structural Relations of the Wisconsin Zinc and Lead Deposits. *Econ. Geol.*, vol. 1, pp. 233–242, 1906; Wis. Geol. and Nat. Hist. Survey *Bull.* 14, 1906.

he may indicate the more favorable places to look for them, and in a district where rocks are adequately exposed at the surface or where underground workings are extensive, structural studies are almost certain to yield data that will aid in prospecting and developing the district. The narrow study of the deposits themselves without regard to the structure of the region that contains them is likely to lead to error.

The laws controlling superficial alteration and the development of secondary ore shoots are by no means simple, but they are more easily interpreted than those controlling the deposition of primary ore shoots. These laws are treated in Chapter XV (pages 124 to 169). They should be constantly in the mind of one who is seeking to ascertain the causes for the occurrence and distribution of the primary ores and of ore shoots in a mining district.

CHAPTER XII

DEFORMATION OF ORE DEPOSITS

The treatment of ore deposits in this volume recognizes three groups of processes—the deposition of ore bodies, the deformation of ore bodies and the superficial alteration and enrichment of ore bodies. Many ore deposits, however, have not been deformed, and a considerable number are not appreciably enriched by superficial alteration. Some deformed deposits and some that are not deformed are workable, though superficial enrichment has not enhanced their value. Other ore bodies after their deposition have been both deformed and enriched.

Deformation is essentially a physical process, involving mass movement, but it may be attended by some chemical changes. Superficial alteration and enrichment are in the main chemical processes, involving molecular movement, although some mass movement may attend chemical changes. The deformation of ore deposits is merely incidental to the deformation of the containing rocks. Economic investigations, however, are largely studies of the geologic structures of ore-bearing areas, and structural geology warrants a more extended treatment in connection with economic studies than can be given here. For discussions of structural geology the reader is referred to standard textbooks of geology.[1]

The character of primary ore bodies depends in large measure on their depth at the time of their deposition. Depth is a factor no less important in deformation. The earth's crust may be regarded as divided into three zones, characterized by the nature of deformation—a zone of fracture near the surface, where all

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[1] See especially Chamberlin, T. C., and Salisbury, R. D.: "Geology," Vol. I, Processes, 1905.

Leith, C. K., "Structural Geology," 1913.

Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, 1904.

Pirsson, L. V., and Schuchert, Charles: "A Textbook of Geology," vol. 1, Physical Geology, 1915.

Lahee, F. H.: "Field Geology," 1916.

rocks will break; a zone of flowage below the surface, where even the stronger rocks are not strong enough to hold spaces open under the pressures that prevail; and a zone of combined fracture and flowage, between these two, where strong rocks break and weak ones flow. This conception of deformation has been developed principally by Van Hise and Leith.

Rocks differ greatly in crushing strength. Shales will flow at shallow depths; quartzites and igneous rocks are strong enough to hold fractures open several miles below the surface. The zone of combined fracture and flowage is of great extent, embracing most of the zone that comes under human observation.

Faulting is characteristic of the zone of fracture, and in areas of rocks deformed at shallow depths normal faults are generally more common than reverse faults, although the latter are not unknown, even at the surface. In the zone of combined fracture and flowage thrust faulting or reverse faulting is conspicuously shown. In the zone of flowage close folding is characteristic. There are great areas in the United States where normal faulting is common and reverse faulting with folding is rare, and other areas where folding and thrust faulting are common and normal faulting is practically unknown. Thus there are deformation provinces, each characterized by a certain type of deformation, just as there are petrographic provinces and metallogenic provinces.

CHAPTER XIII

FAULTING AND FOLDING OF ORE DEPOSITS

FAULTING OF ORE DEPOSITS

General Features.—Faulting is a process of great interest in economic geology, because some ore deposits occur along faults and many are displaced by faults. The mineralization of faults is discussed on pages 192–196. The present chapter is concerned principally with faulting as a process of deformation of rocks and ores. The subject presents many difficulties. We do not know the nature of all the stresses that result in faulting or what becomes of faults as they pass downward, yet by detailed mapping of districts it may be possible to follow faulted ore bodies and predict their position accurately. At Butte, Mont., the complexity of the faulting is appalling; yet, equipped with abundant data gained through years of careful mapping, the geologists of the companies that operate there are enabled to locate ore bodies with great precision in advance of exploration. In many districts the data are sufficient to work out systems that aid in exploration.

The various elements of faults and their nomenclature have recently been discussed in considerable detail.[1] In 1909 the Geological Society of America appointed a committee to investigate the subject. This committee has recommended a comprehensive nomenclature,[2] the adoption of which would bring about

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[1] Spurr, J. E.: "Geology Applied to Mining," 1904. The Measurement of Faults. *Jour. Geol.*, vol. 5, p. 723, 1897.

Ransome, F. L.: The Direction of Movement and Nomenclature of Faults. *Econ. Geol.*, vol. 1, p. 777, 1906.

Tolman, C. F.: Graphic Solution of the Fault Problem. *Min. and Sci. Press*, 1911. How Should Faults be Named and Classified? *Econ. Geol.*, vol. 2, pp. 506–511, 1907.

Reid, H. F.: Geometry of Faults. Geol. Soc. America *Bull.*, vol. 20, pp. 171–196, 1909.

Chamberlin, T. C.: The Fault Problem. *Econ. Geol.*, vol. 2, pp. 585–601, 704–724, 1906.

[2] Reid, H. F., Davis, W. M., Lawson, A. C., and Ransome, F. L.: Report of the Committee on the Nomenclature of Faults. Geol. Soc. America *Bull.*, vol. 24, pp. 163–186, 1913.

uniform usage of terms and thus aid in the correlation of data. Some of the following definitions and figures are taken from its report.

A *fault* is a fracture along which there has been notable displacement. Any fracture is accompanied by some movement, otherwise there would not be a fracture; but the term "fault" is not applied to movements at right angles to a fracture plane, but only to those where it can be shown that one or the other wall has been moved along the fracture plane (see Figs. 42, 43, 44). Fault problems are in the main simple problems of solid geometry, and many interesting theoretical combinations may be solved as problems of construction. But notwithstanding their mathematical simplicity, the solution of many fault problems in the field is difficult because the data are generally insufficient to show precisely the direction and amount of the movements. Where an ore body is cut off by a fault, only a careful consideration of all the data gained by accurate mapping will suffice, and even then it is not always possible to locate the other end of the faulted body.

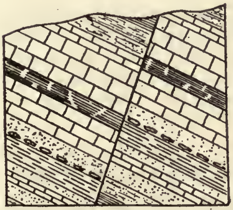

Fig. 42.—Normal fault.

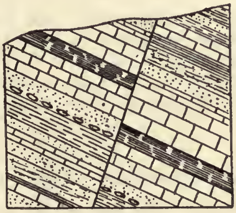

Fig. 43.—Reverse fault.

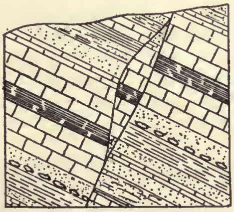

Fig. 44.—Horse in fault.

The *fault strike* is the direction of the intersection of the fault surface with a horizontal plane—that is, a level line along a fault. The *fault dip* is the inclination of the fault surface measured at right angles to the strike on the plane of the fault. The *hade* is the inclination of the fault surface, measured from the vertical; it is the complement of the dip. The *hanging wall* is the upper wall of the fault. The *foot wall* is the lower wall of the fault. A fault block may move perpendicular to the strike of a fault plane, or parallel to it, or its path may make an acute angle with the strike. If one part of the block moves farther in a given direction than another part, the block is said to *rotate.*

There are two ways of defining the displacement caused by a fault: the apparent relative displacement of a bed may be defined by naming the distance between its two disrupted portions measured in any chosen direction, such as the vertical distance between the two portions, measured in a shaft, or the perpendicular distance between the lines of intersection of the two portions with the fault plane; or the actual relative displacement of the two sides in certain directions may be defined. The ap-

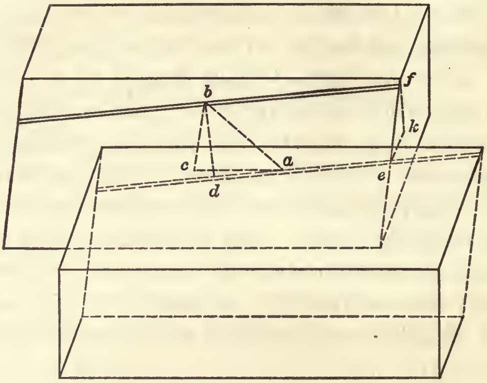

Fig. 45.—Elements of faults. The upper and lower surfaces of the blocks are horizontal; the end faces are vertical and at right angles to the fault strike. *a*, *b*, *c*, and *d* lie in the fault-plane; *e*, *f*, and *k*, in the end face. Let the point originally adjacent to *a* move to *b*; then *ab* = slip or net slip; *cb* = dip slip; *ac* = strike slip; *bd* = perpendicular slip; *ad* = trace slip; *fk* = throw; *ek* = heave.

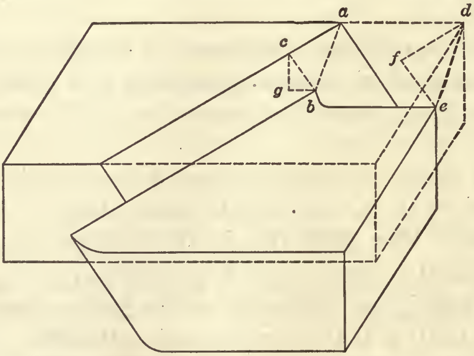

Fig. 46.—Slip and shift. The plane *bcg* is perpendicular to *ac*; *df* is parallel to *ac*. *ab*, slip or net slip; *ac*, strike slip; *bc*, dip slip; *cg*, throw; *bg*, heave; *de*, shift; *df*, strike shift; *fe*, dip shift.

parent displacement is usually measured directly; the actual displacement must generally be worked out later.

The *slip* is the relative displacement of formerly adjacent points on opposite sides of the fault, measured on the fault surface (Figs. 45, 46). The meaning of strike slip and dip slip is indicated on the diagrams. The *shift* is the relative displacement of regions outside the dislocated zone. If the fault is a clean-cut fracture and there is no bending of the strata, the slip and shift are identical. *Throw* and *heave* refer to the displacement of the edge of a disrupted bed, as measured on the vertical section of a block.

"Displacement" and "dislocation" are given no technical meaning but may be applied to a relative movement of bodies on the two sides of the fault, measured in any direction, if that direction is specified, or to the change in position of a bed or other feature, caused by the fault movement (Fig. 47).

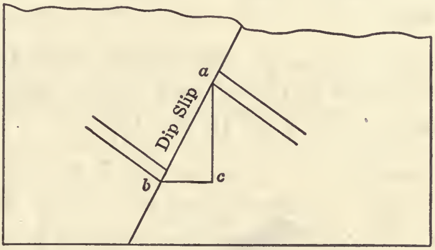

Fig. 47.—Apparent vertical and horizontal displacements. If the section is at right angles to the strike of the fault and the fault movement is down the dip, the dip slip is net slip. *ac*, the vertical component, is the throw; *bc*, the horizontal component, is the heave.

In discussing sedimentary rocks (or other rocks that have planes of reference) the following terms are used:

A *strike fault* is one whose strike is parallel to the strike of the strata. A *dip fault* is one whose strike is approximately at right angles to the strike of the strata. An *oblique fault* is one whose strike is oblique to the strike of the strata. A *bedding-plane fault* is one whose surface is parallel with the bedding of the stratified rocks.

The *separation* of the bed or vein or of any recognizable plane is the distance between the corresponding surfaces of the disrupted bed or other tabular body, measured between corresponding surfaces on the two sides of the fault, in any indicated direction. The *vertical separation* is the separation measured along a vertical line. The *horizontal separation* is the separation measured in any indicated horizontal direction.

The *normal horizontal separation* of a bed or other surface is its horizontal separation measured at right angles to the strike of the bed. It is frequently determined from the outcrops of the bed at the surface of the ground, and is then usually called the offset of the bed (see Figs. 48 and 49).

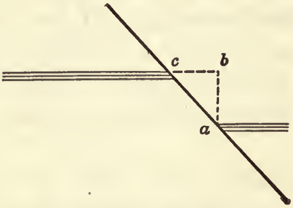

Fig. 48.—Plan of oblique fault. *ab*, offset or normal horizontal separation; *ac*, horizontal separation along fault; *bc*, gap.

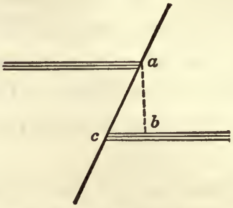

Fig. 49.—Plan of oblique fault. *ab*, offset; *ac*, horizontal separation along fault; *bc*, overlap.

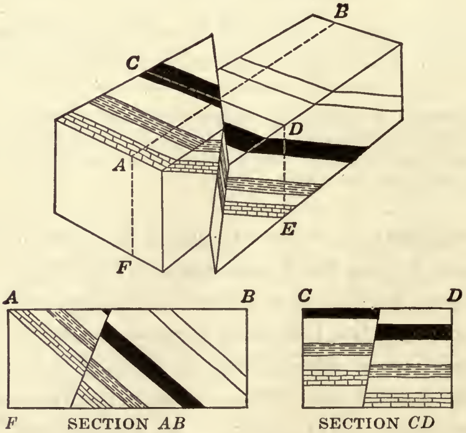

Fig. 50.—Reverse fault due to horizontal displacement.

Normal faults are those along which the hanging wall appears to have been depressed relatively to the foot wall.

Reverse faults are those along which the hanging wall appears to have been raised relatively to the foot wall.

The terms "normal" and "reverse" designate the apparent displacement of the two parts of a dislocated bed or other recognized surface in a vertical plane at right angles to the fault strike. It does not follow that in an oblique fault a horizontal line at right angles to the fault strike would be lengthened if the fault were normal or shortened if it were reverse. This may be illustrated by Fig. 50, which shows an oblique strike fault, apparently reverse, that is formed by horizontal movement. Frequently nothing more than the apparent displacement of the strata can be determined. The terms "normal" and "reverse" faults are used merely for purposes of description and not for the purpose of indicating extension or contraction.

Overthrusts are reverse faults with low dip. In some overthrusts the dip slip is great, amounting to several miles.

A *fault block* is a mass bounded on its sides, completely or in part, by faults. A *horst* is a mass elevated relatively to the surrounding masses and separated from them by faults. A *graben* is a mass depressed relatively to the surrounding masses and separated from them by faults.[1]

A *fault mosaic* is an area divided by intersecting faults into blocks that have settled in varying degrees.

Fault striæ are scratches on the walls of faults formed by abrasion of hard particles. Striæ show the direction of movement along the walls. It is not safe to assume that all the faulting movement was in the direction indicated by the striæ; obviously the last movement only may be recorded. On some faults two sets of striæ cross, showing different movements at different times. *Fault grooves* are undulations deeper than striæ but similarly formed. Because they usually record larger stresses they have greater significance as indicating direction of movement.

Searching for Faulted Segments.—Where detailed mapping does not show the amount or direction of movement along a fault, certain general rules are sometimes applied. These rules are based on experience in different areas and if used intelligently are of much service. They should be applied only when mapping of beds, dikes, or other horizons of reference fails to show the direction of displacement. Fault problems are simple enough if the data at hand are adequate, but for many problems all that can be done is to make the most intelligent use of inadequate data. Four sets of conditions may be considered: (1) faulting of one homogeneous formation, (2) faulting of flat tabular bodies,

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[1] The material beginning at this point is not taken from the report of the committee cited on page 102.

(3) faulting of inclined tabular bodies, (4) faulting of intersecting bodies.

1. If faulting has dislocated a homogeneous body—for example, a great uniform mass of igneous rock—it may not be possible to show even approximately how much movement has taken place. The walls of fissures may be striated or scratched by hard particles rubbing against them, or they may be "case-hardened" or "slickensided" by attrition, or rounded boulders or friction breccia may be found in and along the fissures. All these features suggest that there has been movement parallel to the fissure, although it is not possible to prove any displacement because there are no horizons of reference. Here there is a noteworthy difference in nomenclature that grows out of the natural limitations of field study. In surface mapping of areas that do not contain mineral deposits as a rule only fissures that show displacement are mapped as faults, because friction breccia, slickensiding, and striated faces are not so readily discovered at the surface. But underground, where fresh rocks are more generally exposed, these evidences of movement may be conspicuous, and although there is no way of measuring the movement, many investigators will term a fissure that shows them, a fault.

Suppose that a vein in a homogeneous rock, say in granite, is cut off at a fault. It is important to find the other part of the displaced ore body. Such problems come up frequently in many districts. If the fault involves other veins or several rocks, detailed mapping of the surface or underground may show both the direction and the amount of separation. If the fault involves no other rocks or ore bodies, mapping will not suffice. A short drift along the fault may show that the faulted end of the vein is curved (Fig. 51), and obviously this curved end will point toward the other part of the vein. Again, in one direction from the ore body the fault zone may carry "drag ore" or crushed and brecciated vein matter (Fig. 52), whereas in the other direction it may be barren. On many faults, however, the vein is not curved near the break, and on some no drag ore is shown; still others may show drag ore along the fault in both directions as it is followed away from the ore body. Under these conditions, in regions where normal faults prevail,[1] exploration is directed

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[1] In the western United States most of the faults that displace the Tertiary ores are normal faults.

on the assumption that the fault is normal—that is, that the hanging wall of the fault has dropped. This rule is justified by experience. A tabulation of all faults that involve the ore bodies in a number of regions of Tertiary ore deposits shows that more than 85 per cent. are normal faults. At Butte, Mont., and in some other districts, however, some of the veins are cut off by reverse faults. Each district presents a separate problem.

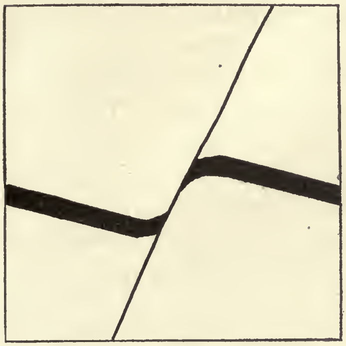

Fig. 51.—Vein curved near fault.

Fig. 52.—Drag ore along fault zone.

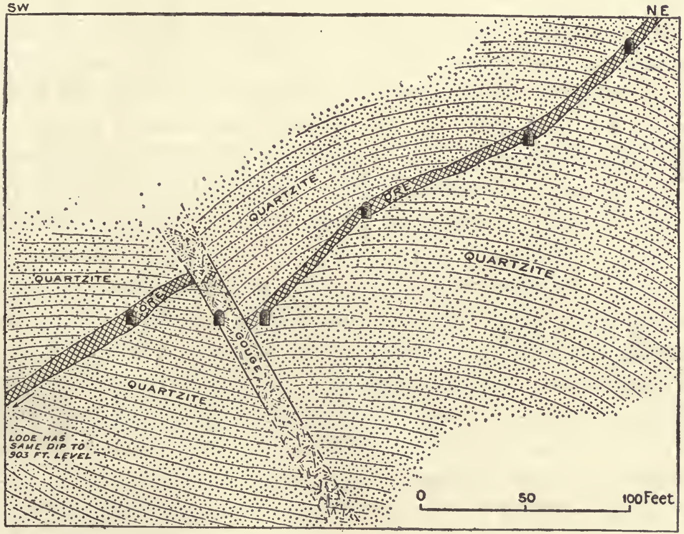

Fig. 53.—Duplication of vein by faulting. On one level parallel drifts are run on the same vein. The fault is a broad zone.

Many faults are not clean-cut fissures but closely spaced parallel fractures along which the movement has been distributed (Fig. 53). Commonly much material is ground up in such a zone, and waters attacking such material will alter it to "clay," making it slippery and "heavy" ground. At some places it is difficult to hold up this ground, and for this reason drifting along faults is avoided in some mines as far as practicable. It is common practice to drive a drift through the fault, continuing it beyond in the direction the vein would take if it were not faulted, and then to crosscut to one side or the other for the vein.

In many districts there is a kind of rhythmic succession of faults, the planes of a system being nearly parallel and the spacing, throws, and displacements of several faults are of the same order of magnitude. Conspicuous examples may be seen at Tonopah (Wandering Boy and Montana-Tonopah veins) and Bullfrog, Nev.

The relations reviewed above emphasize the importance of detailed mapping, even in an area of a homogeneous rock, before extensive exploration is undertaken to find a faulted vein.

2. In flat-lying bedded rocks there are horizontal planes of reference, and all movements that are not in the planes of the beds are shown. Movements parallel to the beds will not be recorded by offset and can not be measured except where some crosscutting feature, such as a dike or an older fault, is involved in the movement. Faults in flat-lying beds are generally normal. Not all faulting movements are directly downward along the plane of the fault—that is, at 90° to the strike of the fault. There may be a horizontal element, as shown along the fault plane by fault striæ that are inclined to the dip of the plane, indicating that the downward pull of gravity was accompanied by lateral stress. As lateral stress is generally relieved partly by tilting or folding the beds, it is generally safe to assume that if beds are flat after faulting, the faults have been normal and there has not been much horizontal movement.

3. Areas of tilted bedded rocks may contain either normal or reverse faults. Faulted beds are generally tilted (Fig. 54) or folded.

In tilted beds faults are marked by offsets of the beds except where the planes of movement are parallel to the beds. The greater the angle between the bedding planes and the fault the greater will be the apparent displacement with the same movement. The problems of this group are often more difficult than those of the groups discussed above, because the faults commonly lie with the beds (Fig. 55) or make only small angles with them. As a rule in field practice it is possible usually to identify only beds or horizons. It is an exception when a particular point on a bed on one side of a fault can be correlated with a corresponding point on the other side, and when the cross section is studied the ends that are separated along the fault are commonly regarded as having joined before the faulting. This assumption is warranted only in areas where the fault movements are at

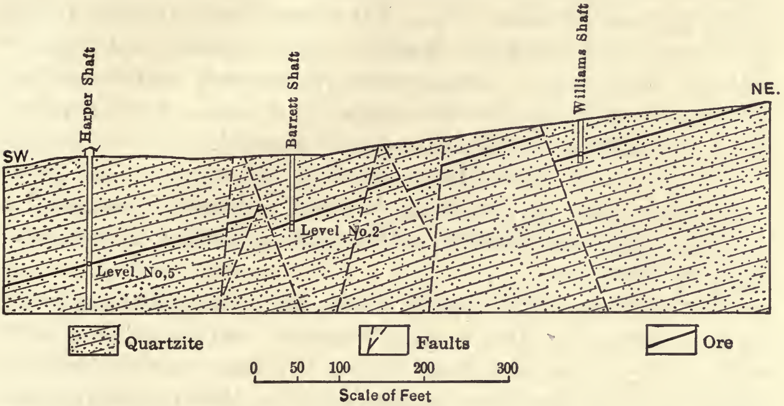

Fig. 54.—Section of bedding-plane deposit cut by normal faults, Combination mine, Philipsburg quadrangle, Montana.

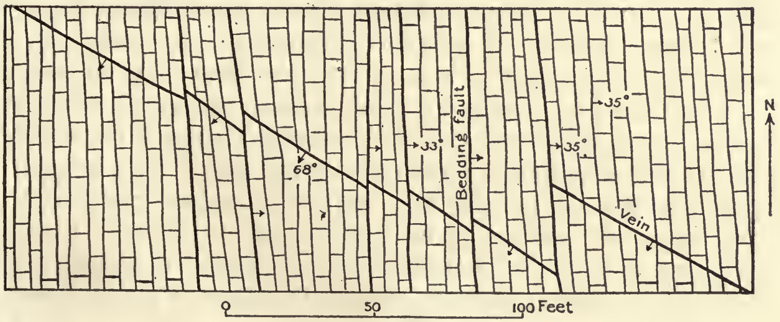

Fig. 55.—Plan of Headlight vein, near Philipsburg, Montana. The vein cuts across the bedding of the country rock and is displaced by faults that follow the bedding plants.

right angles to the strikes of the faults and on sections also normal to the strike. In such areas fault striæ would all be parallel to the dip, but the areas where such conditions exist are in the minority. Here, again, the investigator may profit by study of other faults in the same area. If it is found that all other faults in the area are normal it is highly probable, though not certain, that the fault under consideration is normal, and if in the absence of striæ on the fault plane it is found that on other faults in the area the striæ are nearly parallel to the dip, or if structural studies show that horizontal movement is not great along other faults in the area, the most probable hypothesis is that the downward element is the most important in the fault under consideration.

A fault that is located exactly on the wall of a tabular ore body can not displace it. But as most "tabular" ore bodies, so-called, bend more or less, and most faults also have curved planes, a fault that is at most places parallel to a thin ore body may terminate the ore body by even a slight bend. It is good practice to drift along or (in heavy ground) near such a fault and to crosscut in the walls at short intervals. Strike faults are characteristic of areas of close folding and thrust faulting, and they are by no means rare in regions where normal faulting predominates.

4. The intersection of two planes is a line. Sedimentary beds cut across by veins or dikes or containing "ribbons of ore" may afford horizons of reference marked off by lines. If a fault cuts across such a line, all the elements may be determined after the two parts of the line or linear ore body have been found. In field practice, however, the end of a line is more difficult to discover than a plane or tabular body. The approximate direction of faulting may readily be determined, but to determine the amount of faulting is more difficult. Unless numerous horizons of reference and numerous exposures are available, the task of finding the faulted segment of a small linear body is almost hopeless. Where tabular masses are faulted, however, the problem is to find the plane or zone that may carry ore rather than the exact points or lines that are cut by faults. In homogeneous rocks, where "lines" or "ribbons" of ore are faulted, striæ may show the direction of movement but not its amount. Where this set of conditions prevails the limitations of field study are obvious.

FOLDING OF ORE DEPOSITS

When rocks are broken in blocks and faulted, they are generally tilted and commonly they are flexed or folded. Rocks may be folded in the zone of fracture by movement along many small faults or along joints. This is commonly the case where brittle rocks are deformed near the surface. If rocks containing ore deposits are folded in the zone of fracture, any deposits of brittle minerals they contain, such as quartz, will be folded by fracture.

When rocks are folded in the zone of flowage there is a movement of their minute particles attended by recrystallization and changes in the thickness of the beds.[1] In the zone of flowage the mineral character of the beds or deposits is generally extensively altered. These changes, due to folding in the zone of flowage and recrystallization, are phenomena attending dynamic metamorphism of the rock or ore body. Folding may take place without dynamic metamorphism, but dynamic metamorphism is practically always attended by much folding. Deformation of ore deposits by folding in the zone of flowage is treated in Chapter XIV, on the dynamic metamorphism of ore deposits.

[1] Leith, C. K.: Structural Geology, p. 109, 1913.

Van Hise, C. R.: Principles of Pre-Cambrian Geology. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 1, pp. 631–664, 1896.

CHAPTER XIV

DYNAMIC METAMORPHISM OF ORE DEPOSITS

General Character.—Any ore deposit, however formed, may be metamorphosed by dynamic processes. The terms "dynamic metamorphism," "regional metamorphism," and "dynamo-regional metamorphism" are frequently used interchangeably in describing these processes. "Regional metamorphism" is often used to imply that a considerable body or mass of rocks is affected. As deep burial and pressure are necessary conditions for dynamic metamorphism, it follows that the processes are not selective and that all rocks which were present within the metamorphic mass at the time of dynamic metamorphism were subjected to pressure, although they generally show the effects of pressure in different ways and in different degrees.

Owing to its loss of heat and to other causes, the earth is shrinking. The central part shrinks more rapidly than the outer portion of the lithosphere. Consequently the outer shell, drawn inward by gravity, must wrinkle in order to fit the interior. As a result the lithosphere or shell is warped or folded to form the mountain ranges; the rocks are subjected to great stresses, acting horizontally, or rather tangentially, along the great circles of the earth. Rocks that are not deeply buried may be broken into huge blocks, and at the surface of the earth these blocks are moved about more or less freely as independent masses. Consequently fracturing and faulting take place on a large scale when the rocks near the surface are deformed by compressive stresses.

Rocks that are deeply buried are held down by the superincumbent load and can not move about so freely as independent blocks. At great depths, or where the overlying load is sufficiently heavy, the stresses are greater than the crushing strengths of the rocks, which, however, vary greatly,[1] as is shown by the following table:

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[1] Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, pp. 1011–1013, 1904.

Leith, C. K.: Rock Cleavage. U. S. Geol. Survey *Bull.* 239, 1905.

	Pounds per square inch
Granite	15,000 to 30,000
Sandstone	8,000 to 12,000
Limestone	3,000 to 14,000
Shale	1,000 to 3,000
Clay and mud	0 to 500

Strong granite, which weighs about 165 pounds a cubic foot, is rigid enough to bear a mass of granite about 5 miles high. If factors like differential strains and the weakness of mortar are disregarded, a block of granite in the lower course of a stone monument would theoretically bear the strain of the weight of 5 miles of granite above it. But if a sufficient weight were placed above it, the lower course would fail. Sandstone and limestone would fail under much lighter loads, and shale would fail under a load lighter still. When a rock is so deeply buried that the weight above it exceeds its crushing strength, open spaces or continuous fractures will be closed by the failure of the rock, which acts somewhat as a viscous mass and is said to be deformed by "flowage."

At considerable depths rocks will hold spaces open under greater pressures than near the surface, because their openings may contain water, and the water pressure counterbalances some of the pressure on the rocks. When corrections are made for this factor and for increased rigidity due to lateral support,[1] it appears that while some shales may flow at depths less than 1,500 feet, the strongest rocks would probably not flow at depths of considerably more than 6 miles.[2] If a mass composed of several formations that differ in strength is deformed by pressure, some of the rocks may flow while others fracture (see Fig. 56). The rock mass is then in the zone of combined fracture and flowage.[3] This is a deep zone; as already stated, some clays and shales will flow almost at the surface, but granite and other strong rocks might fracture rather than flow at depths of several miles. Very commonly masses composed of rocks of two or

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[1] Adams, F. D.: An Experimental Contribution to the Question of the Depth of the Zone of Flowage in the Earth's Crust. *Jour. Geol.*, vol. 20, pp. 97–118, 1912.

[2] Leith, C. K.: "Structural Geology," p. 3, 1913.

Van Hise, C. R.: Principles of North American Pre-Cambrian Geology. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 1, pp. 581–845, 1896.

[3] Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, p. 748, 1904.

more kinds will, after deformation by pressure under load, exhibit structure characteristically found in the zone of combined fracture and flowage. The crushing strength of ore bodies depends upon the component minerals and their arrangement. In general ore bodies are stronger than argillaceous rocks (see Fig. 56).

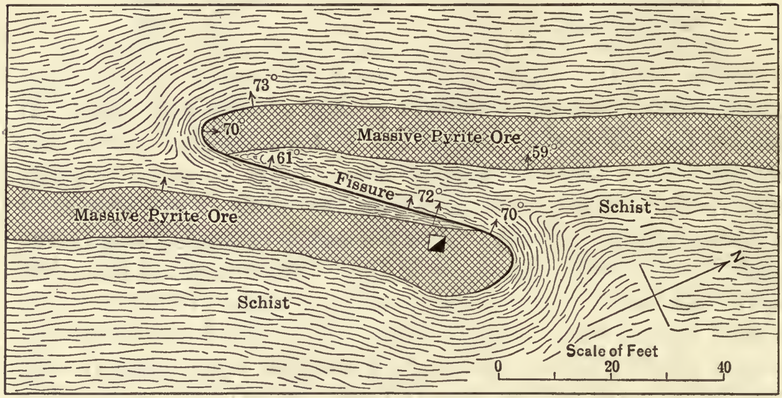

FIG. 56.—Plan of part of 115-foot level, Milan mine, New Hampshire. The pyritic quartzose copper ore fractured while the mica schist "flowed."

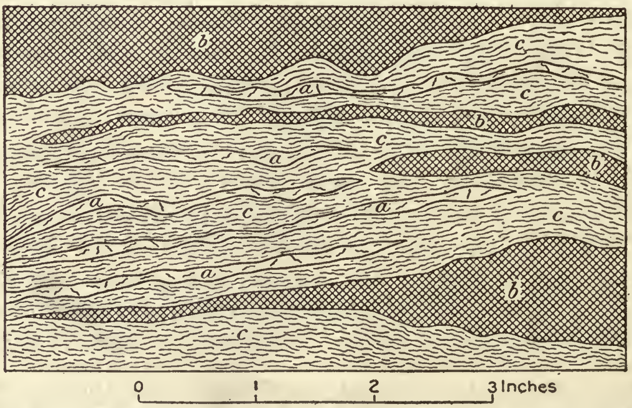

FIG. 57.—Sulphide ore metamorphosed by pressure. *a*, quartz; *b*, pyrite; *c*, chlorite schist.

Rocks that are deformed under great load by pressure (anamorphism) undergo certain characteristic changes. The brittle minerals, such as quartz and feldspar, are mashed, cemented, and recrystallized. Mica, chlorite, and amphibole are generally developed. These platy or fibrous minerals are arranged generally with their long dimension normal to the direction of greatest pressure, thus giving the rock schistosity or slaty cleavage (see Fig. 57). Extensive recrystallization may take place, with the development of garnet, staurolite, ottrelite, andalusite, and other heavy silicates. These minerals are sometimes called the "porphyritic minerals" of schist, and in many schistose rocks they are not arranged parallel to the schistosity. The processes of anamorphism are treated at length by Van Hise, Leith, and others in papers cited above.

Orientation of Ore Bodies.—Elongated or flat minerals show a strong tendency to be oriented with the longer dimensions parallel to the direction of least pressure, and the same tendency is shown by ore bodies that are inclosed in yielding rocks. Quartz veins are broken into smaller bodies which generally lie approximately with the schistosity. In an area that is undergoing metamorphism and that contains quartz veins striking in several directions, the veins which strike across the direction of least pressure are more likely to be broken into smaller bodies than those which lie nearly in the direction of least pressure. In the Ducktown district, Tennessee, and in the Ellijay quadrangle, Georgia,[1] the schists contain thousands of small quartz masses many of which are probably portions of ruptured veins. At a few places these veins are bent into sharp folds, but generally they are broken to form short lenticular or spindle-shaped masses, some of them not much longer than they are wide. A number of quartz lenses in alignment with the schistosity, and approximately in line, may represent the separated portions of larger masses.

Large, thick masses of the harder rock may not be broken apart, and separated, but will generally be lengthened in the direction of the schistosity.

Dynamically metamorphosed deposits may have been faulted near the surface before they were deeply buried; they may have been faulted after any part or all of the great load of overlying rock was removed by erosion; or they may have been faulted when the deposits and the inclosing country rock were in the zone of combined fracture and flowage. Faults formed in the zone of combined fracture and flowage should not penetrate the

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[1] Phalen, W. C.: On a Peculiar Cleavage Structure Resembling Stretched Pebbles near Ellijay, Georgia. *Jour. Geol.*, vol. 18, pp. 554–564, 1910.

weaker or "incompetent" rocks for any considerable distance, but such rocks may flow along the plane of separation. If flowage has occurred it may generally be shown by mapping the schistosity of the country rock along the fault and especially at the two ends of the broken ore body. In the Milan mine, New Hampshire, a fault laps around both ends of the displaced ore body much like the letter S, and it does not penetrate the walls of schist beyond the two ends of the broken ore body (Fig. 56). In the schists the fault is tight. If the area containing the ore bodies had been subjected to more intense deformation after faulting, doubtless the evidence of faulting, which is now preserved, would have been obliterated in the schists between the two ends.

Ore bodies in the shape of carinate folds, and close folds of the commoner types may have been metamorphosed by pressure or they may have replaced older tabular beds that were metamorphosed. The deformation of rock masses composed of formations of various strengths is discussed by Willis,[1] and by Leith and Mead.[2] In experiments with layers of different waxes under pressure Willis produced structures resembling those exhibited by some dynamically metamorphosed ores.

Chemical Changes During Metamorphism.—When ore bodies under load are subjected to heavy stresses great changes may take place, but they probably do not involve the introduction of large amounts of material. This view is not shared by those who regard the "segregated vein" as a body of ore brought together during dynamic metamorphism by solutions searching great masses of rock and concentrating in a smaller mass the metals which before metamorphism were widely scattered through the great masses.

Bastin[3] has taken averages of hundreds of analyses of shales, slates, pelites, and schists and found certain clearly expressed chemical relations which recur throughout the different series, exhibiting various degrees of metamorphism. His averages of analyses indicate that little material is added. The mineral changes are due to rearrangement of the elements of the shale or

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[1] Willis, Bailey: The Mechanics of Appalachian Structure. U. S. Geol. Survey *Thirteenth Ann. Rept.*, part 2, pp. 211–281, 1892.

[2] Leith, C. K., and Mead, W. J.: "Metamorphic Geology," pp. 161–168, 1915.

[3] Bastin, E. S.: Chemical Composition as a Criterion in Identifying Metamorphosed Sediments. *Jour. Geol.*, vol. 17, pp. 445–472, 1909.

slate rather than to the introduction of new elements. Although these investigations indicate that there is but little gain of material during dynamic metamorphism of aluminous sedimentary rocks, a loss of material may take place during metamorphism, especially losses of the more soluble substances, such as lime carbonate.[1]

Although the ore and gangue minerals have a greater crushing strength than the aluminous minerals of quartzitic shale and are therefore more competent to hold spaces open, the same principles will probably apply to them. The processes which operate in the regional or dynamic metamorphism of ore bodies are solution, reprecipitation, mashing, dehydration, deoxidation, and cementation. These changes are attended by the formation of complex minerals of high specific gravity that occupy less space than simple minerals. The elements are rearranged within the ore body; there may be losses, but probably little material is added. However, where igneous bodies intrude rocks at great depths under heavy load, igneous metamorphism may take place, and it may be attended by the addition of much material. Many investigators believe that waters from deep sources migrate considerable distances through rocks deeply buried in the zone of flowage.

Mineral Composition.—As deposits of any character may be metamorphosed by pressure, the metamorphosed deposits contain a great variety of minerals. Many of these minerals were doubtless formed by primary processes and have endured throughout the metamorphic changes, but others have been formed while the deposits have been deeply buried and compressed. Garnet, chlorite, epidote, zoisite, mica, and amphibole are very commonly present. Even if they do not occur in the primary deposits, one or all of them may be formed during metamorphism. The sulphides are probably little changed, at least in kind. By dehydration and reduction, hematite and magnetite are assumed to be developed. By some investigators pyrrhotite is believed to be characteristic of these deposits,[2] but in some of the metamorphosed pyritic deposits it is lacking.

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[1] Leith, C. K., and Mead, W. J.: "Metamorphic Geology," p. 226, 1915.

[2] Klockman, F.: Ueber den Einfluss der Metamorphose auf die mineralische Zusammensetzung der Kieslagerstätten. *Zeitschr. prakt. Geologie,* vol. 2, pp. 13, 153, 1904.

Texture and Paragenesis.—When rock matter is metamorphosed by heavy pressure in the zone of flowage it tends to become schistose. The particles of hard minerals, such as quartz, may be rotated and oriented so that their short dimensions lie in the direction of greatest stress; new crystals will form, and their short axes also will lie in the direction of greatest stress. The micas, chlorites, amphiboles, and other platy or fibrous minerals, all lying with their greater dimensions parallel and also parallel to the long dimensions of quartz or other hard minerals, give character to the schistose texture or slaty cleavage.[1] Although some ores show schistose texture it is not so commonly developed in perfection in them because micaceous or fibrous minerals are less common in metamorphosed ore bodies than they are in many metamorphosed rocks. Most of the sulphides, moreover, recrystallize readily, and continued metamorphism will cause recrystallization and obliteration of any schistose texture that may have been previously formed. In certain metamorphosed pyritic bodies of Maine and New Hampshire, contained in chloritic schists, the ore near the margins of the deposits is composed of quartz, pyrite, and chlorite and shows a well-defined schistosity (Fig. 57). The central portions of the lodes, which are composed of quartz and pyrite without chlorite or other platy or fibrous minerals, show no schistosity whatever, although the pyrite when

Fig. 58.—Polished surface of schistose ore metamorphosed by pressure, Milan mine, New Hampshire.

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[1] Leith, C. K.: "Structural Geology," p. 76, 1913.

examined microscopically is seen to be shattered and recemented.[1] If two sulphides like chalcopyrite and pyrite are present, these may be mashed and partly recrystallized to form a banded ore—a sulphide schist (Fig. 58). If the flaky or fibrous materials, such as mica, chlorite, and amphibole, are contained in the ore, these will generally be oriented parallel to the direction of schistosity in the country rock. Garnet bands may be extensively shattered (Fig. 59).

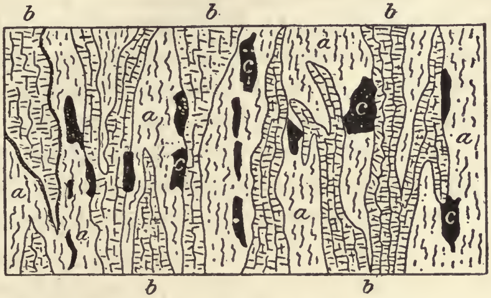

Fig. 59.—Schistose ore from Deer Isle, Maine, showing parallel bands of garnet, chlorite, sericite, and sulphides. *a*, Chorite and sericite; *b*, fractured garnet; *c*, pyrite, zinc blende, and galena.

When an association of minerals has been compressed under a load sufficient to permit the softer minerals to flow and the harder and stronger minerals to break, the soft minerals will fill cracks and cement the fractured particles of the harder minerals.

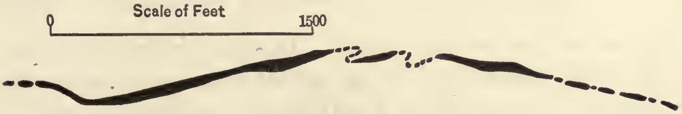

Fig. 60.—Plan of ore deposit at Rammelsberg, Germany.

Adams,[2] in a series of experiments on deformation, placed various crystals in strong tubes which were filled with wax or some other plastic substance before they were sealed. Under great pressure the softer minerals were deformed by flowage and recrystallization. The ease with which flowage structure was

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[1] Emmons, W. H.: Some Ore Deposits of Maine and the Milan Mine, New Hampshire. U. S. Geol. Survey *Bull.* 432, p. 19, 1910.

[2] Adams, F. D.: An Experimental Investigation into the Action of Differential Pressure on Certain Minerals and Rocks, Employing the Process Suggested by Prof. Kick. *Jour. Geol.*, vol. 18, pp. 489–525, 1910.

produced was found to vary inversely with the hardness of the minerals.

In the Rammelsberg deposits, in the Harz Mountains, Germany (Figs. 60, 61), the soft sulphides, sphalerite, chalcopyrite, galena, and arsenopyrite, are pressed out in streaks and squeezed around the harder pyrite masses; the structure is like that of a gneiss.[1]

Ore bodies, like rocks, have doubtless suffered all degrees of dynamic action. In some the minerals may be merely cracked and bent. In others, where material for forming platy or fibrous minerals was available and where pressures were sufficient, the ore may have become schistose. High temperature and pressure cause sulphides to recrystallize, and as the most common of these are approximately isodiametric, the crystals do not readily produce a schistose texture. In sulphide deposits schistosity is doubtless developed in the earlier stages of metamorphism. Subsequently, if pressure and heat become sufficiently great, the sulphide ore will recrystallize and schistosity will be destroyed.

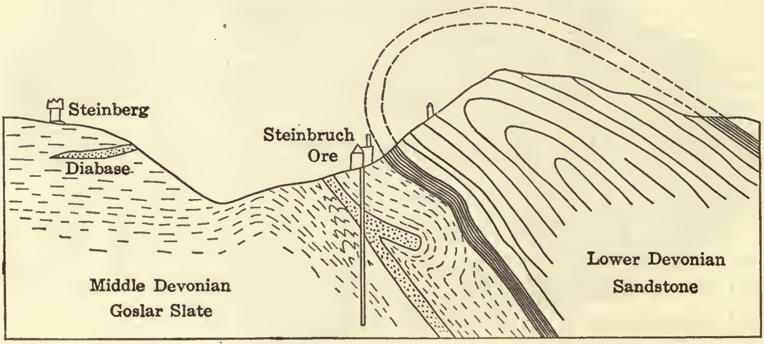

FIG. 61.—Cross-section showing ore deposit at Rammelsberg, Germany.

Dynamically metamorphosed sulphide deposits rarely show vugs lined with banded crusts. If the wall rock was hydrothermally altered when the primary ores were formed, the platy hydrothermal minerals, such as mica and chlorite, will be recrystallized and, by pressure, oriented so that their longer axes lie in the direction of the schistosity of the region.

Deposits Inclosed in Schists but not Dynamically Metamorphosed.—Many ore bodies in schists have not been meta-

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[1] LINDGREN, WALDEMAR, and IRVING, J. D.: The Origin of the Rammelsberg Ore Deposit. *Econ. Geol.*, vol. 6, pp. 303–313, 1911.

morphosed. They were deposited after the metamorphism of the schists and do not exhibit the structure characteristic of metamorphosed deposits. Some districts of schistose rocks contain deposits formed before metamorphism and also deposits formed after metamorphism. In New England[1] both types of deposits are represented.

Age Relations of Dynamically Metamorphosed Deposits.—As deep burial is necessary for dynamic metamorphism, the older rocks and ores are more commonly affected by such processes than the younger rocks and ores, which in general have not been so deeply buried. Ore deposits formed in late geologic time at moderate and shallow depths are rarely metamorphosed by dynamic processes. But deposits formed in earlier geologic time, even at the surface, may after deep burial be intensely metamorphosed by pressure; some of the iron ores of the Vermilion district, Minnesota, and of the Marquette district, Michigan, that were concentrated by surface weathering, have been deeply buried and converted by pressure into schistose hematites.

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[1] Emmons, W. H.: Some ore deposits of Maine and the Milan mine, New Hampshire. U, S. Geol. Survey *Bull.* 432, pp. 14–22, 1910.

CHAPTER XV

SUPERFICIAL ALTERATION AND ENRICHMENT OF ORE DEPOSITS

General Features.—The earth is commonly regarded as composed of a core—the lithosphere—surrounded by two shells, the hydrosphere and the atmosphere. The atmosphere or air contains also water, and the hydrosphere, or water sphere, contains some air. Both air and water penetrate the lithosphere. Weathering results where rocks, air, and water come together—where rocks of the lithosphere are attacked by air and water.

Rocks and ores exposed to air and water at or near the surface of the earth break down and form soluble salts and minerals that are stable under surface conditions. Few minerals that are long exposed to air and water remain unaltered; some, however, are much more resistant to weathering than others and these become concentrated when material associated with them is removed. Weathering usually precedes erosion, and many valuable beds, such as clay, sand, iron ore, and placer gold, become concentrated through weathering and aggradation working together. The subject treated here is the weathering of material in place, and particularly the leaching, and enrichment of mineral deposits by weathering.[1]

By weathering, many low-grade ores and protores are converted into valuable deposits. Enrichment may be brought about by solution and removal of valueless material, leaving the weathered material in a more concentrated state; or it may be brought about by solution of valuable materials and their precipi-

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[1] For more extended discussions of rock weathering the student is referred to the following papers:

Merrill, G. P.: "Rocks, Rock Weathering, and Soils," 1897.

Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, 1915.

Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, 1903.

Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, 1917.

Leith, C. K., and Mead, W. J.: "Metamorphic Geology," 1915.

Watson, T. L.: The Granites of Georgia. Ga. Geol. Survey *Bull.* 9–A, 1903.

tation in depth. Some metals are readily dissolved near the surface in oxygenated waters, and are readily precipitated at depths where air is excluded and where the solutions are rendered neutral by reacting on ores and rocks. Many sulphide deposits are leached of metals near the surface but are enriched near the water level where air is excluded and precipitation takes place. Concentration by weathering and related processes is secondary enrichment. Because the chemical process in rocks is notably different from chemical processes in the presence of appreciable sulphides, it is practicable to treat them separately.

Ores formed by the weathering of rocks are ordinarily derived from material of very low grade; many investigators consider them a separate class of primary ore. The geologic processes, however, are closely related to those by which workable sulphide deposits are concentrated from lean, unworkable protore. The material weathered, whether rock or ore, determines the kind and in general the value of the product of weathering. Thus iron ore will result from thorough weathering of iron-rich rocks, such as peridotite, diabase, greenalite, and cherty iron carbonate rocks. Bauxite will form from nepheline syenites and other aluminum-rich rocks. These rocks that are especially rich in certain metals are classed as protores of those metals.

The processes of weathering and also of sulphide enrichment are closely allied to the deposition of ore bodies at moderate depths by cold solutions. There is this difference, however: the ore bodies mentioned are formed at places where no metalliferous rock may have existed previously, and many though not all are formed at or near places where there was some reducing agent such as carbonaceous material. Metalliferous products of weathering and sulphide enrichment occupy in the main the spaces formerly occupied by lower-grade metalliferous material from which the workable deposits were derived. By weathering and enrichment some small bodies of ores may be formed in and along cracks outside of the older parent metalliferous rock, but these are generally of only subordinate importance. They form, however, a gradational type between the secondary deposits and the primary deposits formed at shallow or moderate depths by cold solutions (pages 74 to 83).

WEATHERING OF ROCKS

The term weathering includes all the processes by which rocks near the surface exposed to water and air are gradually decomposed and broken up. These processes are active mainly above the water level. Rain water carries oxygen and some carbon dioxide, which render it an active solvent; changes of temperature, frost, and vegetation loosen the material and render it more permeable. The alkalies in rocks are readily dissolved, especially sodium. Alkaline earths are attacked also, and calcium and magnesium go into solution. Silica dissolves less readily, but the alkalies render the solutions more active solvents of silica. The metals iron and aluminum are slowly dissolved, iron in general more rapidly than aluminum. New minerals are formed, especially oxides, hydroxides, and carbonates; most carbonates, however, are unstable under conditions of thorough weathering.

As a rule the weathering of igneous rocks will increase the volume where expansion is possible,[1] but this increase is only temporary, for by solution material is removed. Most ores that have been concentrated by weathering show much pore space due to the removal of material by solution. In many weathered rocks the pore space amounts to 50 per cent. or more. The development of pore space, however, weakens the rock, and the pore space may be partly eliminated by slumping.

Of the minerals attacked by weathering some are comparatively stable. Gold, platinum, magnetite, chromite, garnet, cassiterite, rutile, monazite, and several others are not readily dissolved and will accumulate in residual bodies and placers. Quartz is not strongly attacked, but the alkali, alkali earth, and iron silicates dissolve more readily. As a general rule the silicates containing little silica, such as olivine and enstatite, will be changed more readily than feldspars, and feldspars more readily than quartz. Consequently the basic rocks—gabbro, peridotite, and others—are the more readily altered. Such rocks on weathering yield many metalliferous products. Kaolin, bauxite, gibbsite, ferric hydroxides, and some manganese oxides are fairly stable under surface conditions, and rocks composed of these minerals are but slowly attacked. Many silicates digested in water give alkaline reactions, and if digested in water charged with carbon dioxide, their loss is very appreciable.

During rock weathering[2] silica is released and carbonates of

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[1] Merrill, G. P.: The Principles of Rock Weathering. *Jour. Geol.*, vol. 4, pp. 704–724, 1896.

[2] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 481, 1916.

lime, iron, magnesia, and alkalies may be formed. The iron carbonate is readily oxidized to ferric hydroxide. The lime, magnesia, and alkali salts remain in solution, to be carried away, together with some silica. The portion of the rock that is not dissolved is hydrated; the feldspars are altered to kaolin, the magnesian minerals to talc or serpentine, and the iron to hydrated ferric oxides; quartz grains are dissolved very slowly.

In the following table are shown analyses of diorite from Albemarle County, Virginia.[1] The concentration of aluminum and iron and the loss of lime, magnesia, and soda are noteworthy. The large loss on ignition of the altered rock indicates extensive hydration during weathering.

Analyses of Fresh and Altered Diorite

	Fresh	Altered
SiO_2	46.75	42.44
Al_2O_3	17.61	25.51
Fe_2O_3 FeO	16.79	19.20
MgO	5.12	0.21
CaO	9.46	0.37
Na_2O	2.56	0.56
K_2O	0.55	0.49
Loss on ignition	0.92	10.92
P_2O_5	0.25	0.29
MnO		
	100.01	99.99

Thorough weathering may convert a basic rock to a mantle of workable iron ore. Such deposits are termed lateritic ores. In eastern Cuba lateritic iron ores are extensively developed.[2] The

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[1] Merrill, G. P.: "Rock Weathering and Soils," pp. 224–225.

[2] Leith, C. K., and Mead, W. J.: Origin of the Iron Ores of Central and Northeastern Cuba. Am. Inst. Min. Eng. *Trans.*, vol. 42, pp. 90–102, 1912. Additional Data on Origin of Lateritic Iron Ores of Eastern Cuba. Am. Inst. Min. Eng. *Bull.* 103, pp. 1377–1380, July, 1915. "Metamorphic Geology," p. 391, 1915.

Kemp, J. F.: The Mayari Iron-Ore Deposits, Cuba. Am. Inst. Min. Eng. *Bull.* 98, pp. 129–154, February, 1915.

Little, J. E.: The Mayari Iron Mines, Oriente Province, Island of Cuba, as Developed by the Spanish-American Iron Co. Am. Inst. Min. Eng. *Trans.*, vol. 42, pp. 152–169, 1911.

deposits cap intrusive bodies (Fig. 62), and are from less than 1 foot to 80 feet thick. They are situated on plateaus from 1,500 to 2,000 feet above sea level. The ore grades downward into serpentine, an altered basic intrusive rock containing only a little bauxite, kaolin, and other minerals. Leith and Mead have calculated the mineral constituents of the ore and determined the amount of pore space at different depths. These data they used in constructing the diagram shown in Fig. 63. Below 29 feet serpentine is encountered. By the removal of magnesia and silica the pore space is much increased near the surface and the serpentine rock, which carries only 7.10 per cent. of iron at a depth of 29 feet, becomes an ore carrying 46.39 per cent. of iron. These and similar changes may be compared with those effected in the alteration of greenalite in the Mesabi range, Minnesota (page 307), and the weathering of nepheline syenite in Arkansas to form bauxite (page 506).

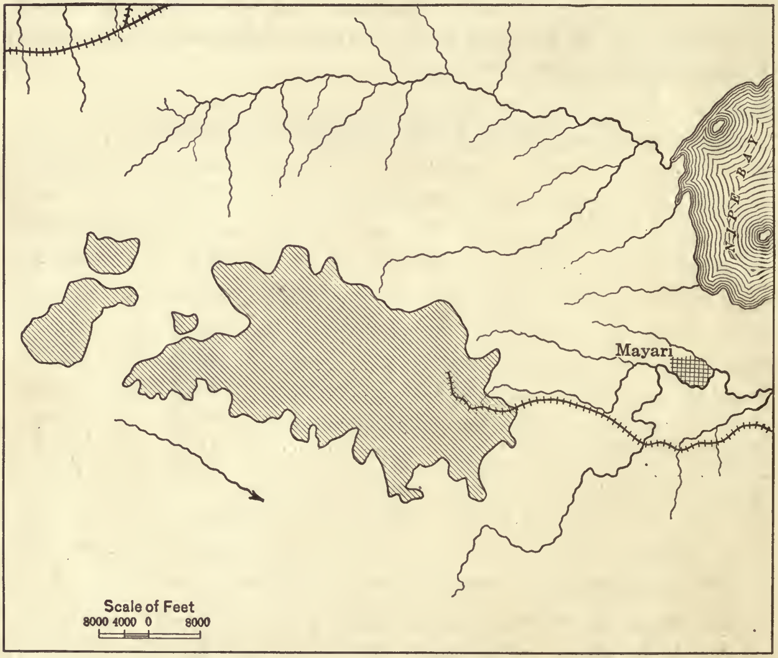

Fig. 62.—Sketch showing limits of ore bodies, Mayari, Cuba. (*After Little.*)

HYDROMETAMORPHISM

Decomposition may take place at considerable depths, below the level of ground water and below the zone of active oxidation. Close examination of many of the rocks that appear nearly fresh shows that uralite, chlorite, serpentine, talc, or hydromica have formed from older silicate minerals. Such changes, which take place below the zone of oxidizing decomposition, are commonly termed "hydrometamorphism." Some basic rocks (peridotites, hornblendites, pyroxenites) are almost entirely converted into secondary minerals, commonly into serpentine. As the surface is worn away the hydrometamorphosed rocks are exposed to actively oxidizing solutions, and more extensive changes take place. Weathering and hydrometamorphism of rocks may be compared respectively to surface oxidation and deep enrichment of sulphide ores.

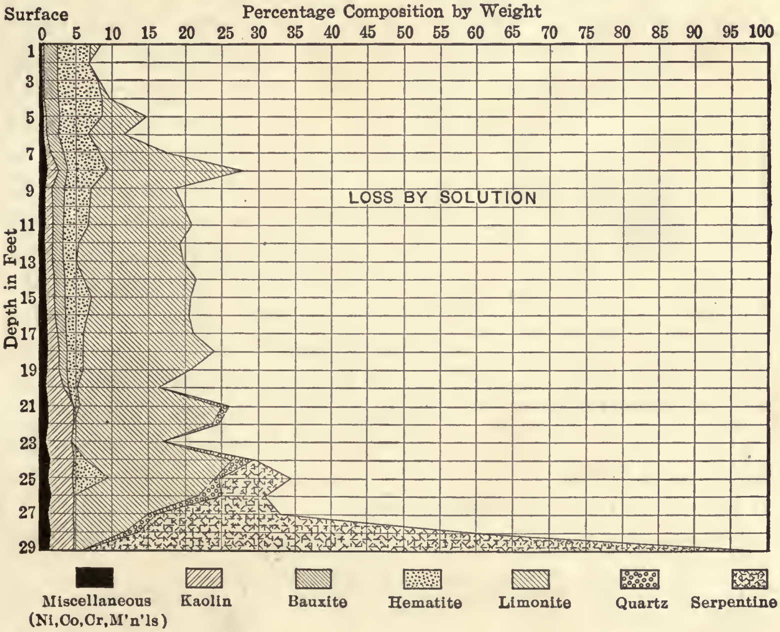

Fig. 63.—Diagram showing mineral changes in alteration of serpentine to iron ore by weathering, Mayari, Cuba. (*After Leith and Mead.*)

SUPERFICIAL ALTERATION AND ENRICHMENT OF SULPHIDE DEPOSITS

General Features.—Many sulphide deposits show characteristic changes from the surface downward.[1] The outcrop and the upper part of the oxidized portion of a deposit may be poor. Below this there may be rich oxidized ore; still farther down, rich sulphide ore; and below the rich sulphides, ore of relatively low grade (see Fig. 64). This lowest ore is commonly assumed to be the primary ore, from which the various kinds of ore above have been derived. The several kinds of ore have a rude zonal arrangement, the so-called zones being, like the water table, highly undulatory (see Fig. 65). They are related broadly to the present surface and generally to the hydrostatic level but may be much more irregular than either, for they depend in large measure on the local fracturing in the lode, which controls the circulation of underground waters. Any zone may be thick at one place and thin or even absent at another. The zone of oxidized ore is generally above the water level. The zone of secondary sulphides in moist countries is in general below the water level.

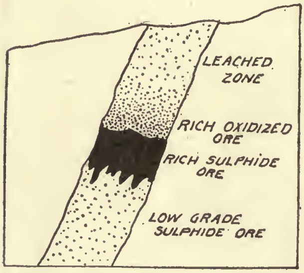

Fig. 64.—Section showing a tabular sulphide ore deposit with changes due to superficial alteration and enrichment.

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[1] Emmons, S. F.: The Secondary Enrichment of Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 177–217, 1901.

Weed, W. H.: The Enrichment of Gold and Silver Veins. *Idem*, pp. 424–448.

Van Hise, C. R.: Some Principles Controlling the Deposition of Ores. *Idem*, pp. 27–177.

Kemp, J. F.: Secondary Enrichment in Ore Deposits of Copper. *Econ. Geol.*, vol. 1, pp. 11–25, 1906.

Ransome, F. L.: Criteria of Downward Sulphide Enrichment. *Econ. Geol.*, vol. 5, p. 205, 1910.

Penrose, R. A. F., Jr.: The Superficial Alteration of Ore Deposits. *Jour. Geol.*, vol. 2, pp. 288–317, 1894.

Tolman, C. F.: Secondary Sulphide Enrichment. *Min. and Sci. Press.*, vol. 106, pp. 38–43, 141–145, 178–181, 1913.

Emmons, W. H.: The Enrichment of Sulphide Ores. U. S. Geol. Survey *Bull.* 529, 1913.

Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, pp. 1–503, 1917.

All these zones except that of the primary ore are, broadly considered, continually descending. Through more rapid erosion at some particular part of the lode any one of these zones may be exposed, and hence an outcrop of ore of any character is possible.

Level of Ground Water.—The terms "water table" and "level of ground water" are generally used to describe the upper limit of the zone in which the openings in rocks are filled with water. This upper limit of the zone of saturation is not a plane but a warped surface. It follows in general the topography of the country but is less accentuated. It is not so deep below a valley as below a hill but rises with the country toward the hilltops and in general is higher there than in the valleys. Although the water in the zone of saturation does not move rapidly, it is not stationary. If there is a lower outlet, it will move toward that point. Its movements are slow, however, and it may follow a very circuitous route before it issues again at the surface. It follows the paths of least resistance, and if these are downward the water may sink to great depths before it rises, under pressure, to make its exit at some point which is lower than that at which it first entered the belt of saturation.

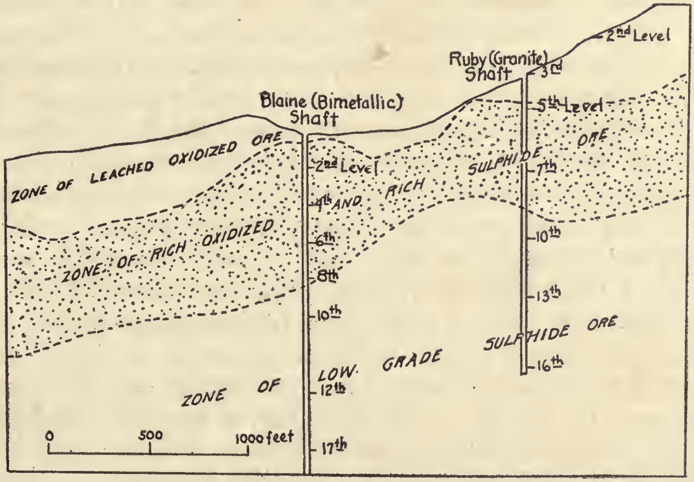

FIG. 65.—Vertical section of Granite-Bimetallic vein, Philipsburg, Montana.

As the country is eroded the water level moves downward and, within certain limits, it changes with the seasons. In dry years it is deeper than in wet years, and in dry seasons it is deeper than in wet seasons. Thus the water table may be considered a kind of indicator that registers the differences between the loss or leakage of the zone of saturation and addition from the surface. There is a zone that is above ground-water level in dry periods but below it in wet periods, and in moist hilly countries this zone may be of considerable vertical extent. The difference of altitude between the top of the zone of saturation in a wet year and in a dry year is normally greater under the hilltops than on the slopes and in the valleys. Thus the water table oscillates, though in general it moves downward with degradation of the land surface (see Fig. 66).

Vadose Circulation.—Of the rain that falls on the surface a part is drained off by rills and streams, another part is evaporated, and still another part soaks deep into the ground, passes downward, and is added to the water of the zone of saturation. The downward movement of such water toward the zone of saturation has been termed the "vadose" circulation (from *vadus*, shallow).[1] The depth or thickness of the vadose zone is variable, for its lower limit depends on the variable level of ground water. In moist hilly countries its depth varies from a few feet to several hundred feet. In arid regions, where the rainfall is low and evaporation is rapid, it may extend to much greater depths. It is, in the main, a zone of solution; consequently its rocks are open and circulation within it is comparatively rapid.

Deeper Circulation.—The circulation of the water in the zone of saturation depends on the relief of the country and on the number, continuity, spacing, and size of the openings in the rocks. Under hydrostatic head the waters in this zone move to points of less pressure and issue at points lower than those of entry. If the deposit is tight and there are no deep outlets the principal movement is shallow, following down the grade of the water table. As a rule movement in the deeper zone is much slower than in the vadose zone, because the openings are less numerous and also because they are smaller, so that friction on their walls is greater. Below the water table, moreover, the openings are already filled with water. As shown in deep mines the under-

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[1] Pošepný, Franz: "The Genesis of Ore Deposits," p. 18, 1902. Pošepný includes in the "vadose" circulation water below the "permanent water level."

ground circulation, in many places is exceedingly sluggish.[1] In some rocks, however, under favorable structural conditions, surface waters are conducted, in porous beds or along fractured zones, several thousand feet below the surface. In other rocks little or no water is collected at depths of more than a few hundred feet.

Region of Nearly Stagnant Water.—The zone of the deeper circulation varies greatly in depth and vertical extent. Its water is discharged at points that are not lower than the lowest altitude of the country, and if numerous points of discharge are located along a lode that crops out at several different altitudes there will be a considerable lateral movement of the waters toward these points, for the solutions move to points of less pressure. If lower rocks are saturated and their openings are filled, the solutions descending from above will find any lateral outlet that is available. Where there are structural features that afford passages like inverted siphons there may be a considerable movement of water below the lowest outlet, but where the spacing of openings along the lode is fairly regular the circulation becomes less and less vigorous as depth increases below the lowest outlet. There is thus a division, probably everywhere somewhat indefinite, between the sluggish deeper circulation and a zone of static or nearly stagnant waters below it. There is much evidence that in some rocks the top of this zone lies within a few hundred feet of the surface or even less, but where there are deep open fissures it may be much deeper.[2]

Pulsating Movements of Underground Waters.—The underground circulation of water is normally downward from the top of the vadose zone to the water table; thence by less direct routes to greater but generally undetermined depths below the water table; after that laterally, and perhaps upward, to openings that are lower than the points of entrance. This circulation, however, is not to be regarded as a uniform, steady flow. Many springs, probably most of those that are fed by underground

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[1] Kemp, J. F.: The Rôle of the Igneous Rocks in the Formation of Veins, in Posepný, Franz: The Genesis of Ore Deposits, pp. 681–809, 1902.

Finch, J. W.: The Circulation of Underground Aqueous Solutions and the Deposition of Lode Ores. Colo. Sci. Soc. *Proc.*, vol. 7, pp. 193–252, 1904.

Rickard, T. A.: Waters Meteoric and Magmatic. *Min. and Sci. Press*, June 27, 1908.

[2] Finch, J. W.: The Circulation of Underground Aqueous Solutions and the Deposition of Lode Ores. Colo. Sci. Soc. *Proc.*, vol. 7, p. 216, 1904.

meteoric waters, issue more copiously during and immediately after rainy seasons than during dry seasons. At times of drought some of them will cease to flow. There are sound reasons for supposing that the normal movement of ground water is not steady, even at depths below the ground-water level. After a rainy season the water level is raised and the additional pressure on the water in the zone of saturation will cause it to move more rapidly to points of less pressure and to issue at any available openings. The water that during a dry season has ceased to issue through springs or other openings but has remained nearly if not quite static will have had a longer time to be attacked by ores and gangue minerals with which it is in contact. At depths where air is excluded acid will be neutralized, and as nearly all rocks give alkaline reactions with water the solutions will tend to become alkaline. Higher up, at and above the water level, where air has access, the solutions will be acid. But after a season of heavy rains the acid water of the higher zones will rapidly encroach upon, mingle with, and tend to crowd out the alkaline waters below, which, of course, issues at the surface where openings are available. Thus we may with good reason assume that certain parts of zones of alteration are alternately in alkaline and in acid environments (Fig. 66).

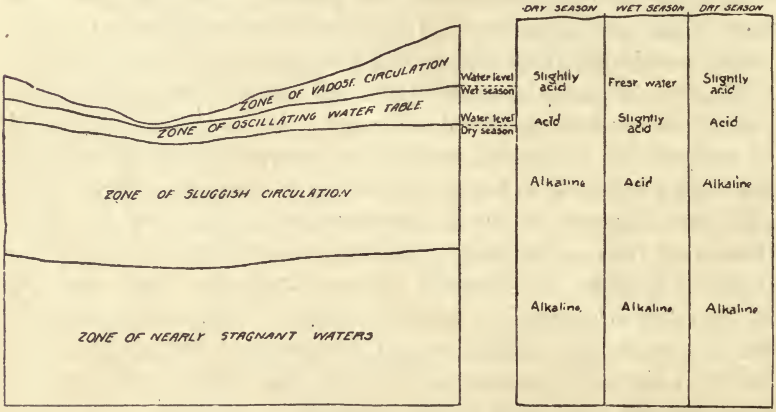

FIG. 66.—Diagram showing water levels and zones of ground water in a relatively moist climate. In part of the zone of sluggish circulation acid and alkaline conditions alternate with seasons.

Physical Conditions that Influence Enrichment.—Enrichment is influenced by many factors, among them permeability, latitude, altitude, and relief.

Permeability is essential for sulphide enrichment. If the primary deposits are not permeable the solutions that pass downward through the oxidized zone will move laterally along the contacts between oxidized and sulphide ores and ultimately will escape into fractures in the wall rocks or reissue as springs at some level below the points of entry. If they do not encounter a reducing environment the metals may be scattered. In deposits that have been shattered by strong movements there is generally more extensive and deeper enrichment than in deposits that have been but slightly fractured. Brittle minerals like quartz and chert fracture readily, and deposits composed largely of the brittle minerals are generally more deeply enriched than deposits of tough or elastic minerals. Many of the heavy silicate-sulphide ores of contact-metamorphic origin that carry a gangue of abundant fibrous amphibole, mica, chlorite, or like minerals do not show sulphide enrichment to great depths.

A warm climate, which favors chemical action, is favorable to weathering and enrichment. Deposits in cold regions are not so likely to show extensive concentration: low temperature decreases chemical activity, and freezing prevents solution. Where the ground is frozen to considerable depths during the winter and thaws out only a short distance below the surface during the summer thorough weathering can not extend to great depths.

As a rule the relief is great in areas of high altitudes, and erosion is consequently more rapid. Moreover, in such areas temperatures are lower and conditions are less favorable to solution. Deposits located at very high altitudes, where rocks are disintegrated by frost and carried away unweathered as talus and boulders, are not so likely to be extensively enriched as deposits that lie at lower altitudes. On the other hand, under some conditions the processes of enrichment are effective at considerable altitudes. Many deposits in Colorado and Montana that crop out at more than 8,000 feet above sea level contain extensive zones of secondary ores.

Strong relief supplies head and is therefore favorable to deep and rapid circulation of underground water, and it is likewise favorable to relatively deep enrichment. In base-leveled regions underground circulation is sluggish, and the nearly stagnant waters can not descend far into the zone of primary sulphides without losing the valuable metals which they dissolve higher up.

Under such conditions enrichment may be practically halted, because the ground-water level becomes nearly stationary, and after the soluble metals have all been dissolved from the oxidized zone solution may practically cease.

As strong relief is favorable to rapid erosion it is unfavorable to thorough leaching. Where erosion is slow the outcrops and upper portions of deposits are exposed to processes of weathering for periods long enough to favor thorough leaching and, if the metals are reprecipitated at lower depths, to favor enrichment. On the other hand, erosion may be delayed to a point beyond which it is unfavorable to solution and precipitation; the downward migration of the zone of oxidation exposes new surfaces to solution, making masses of fresh sulphides available for reconcentration. Consequently where metals dissolve readily, comparatively rapid erosion may favor rapid concentration. The metallic contents of many deposits of secondary ores represent not only what has been leached from the gossan now exposed but also what has been dissolved from portions of the deposits that have been carried away by erosion.

Other conditions being similar, the amount of enrichment must depend on the length of time the deposits have been exposed to weathering and erosion. In general, weathering has acted for a shorter time on late Tertiary deposits than on middle Tertiary, early Tertiary, or Cretaceous deposits. The age of the deposit is not, however, invariably the most important factor in determining the extent of its enrichment, for some of the middle or late Tertiary deposits, such as those in the southwestern part of the United States, show more extensive migration of the metals than is shown by some older deposits that have been exposed to weathering for a much longer time.

Inasmuch as sulphide enrichment depends on the action of surface agencies, it is important to know as far as possible the details of the history of any deposit considered, the length of time it has been exposed to weathering, and whether faulting or folding or a second episode of primary ore formation has taken place since it was first formed. In short, any geologic or physiographic data might have a bearing on the problem of enrichment.

If the present topography is like that which existed when primary deposition took place—and it may be if the deposits were formed in comparatively late geologic time—then the richer ore of the primary deposits may have an obvious relation to the present surface. In some deposits of gold and silver ore the maximum precipitation of the metals appears to have taken place at relatively short distances below the surface that existed at the time of deposition. Thus the primary ore may show a comparatively constant change in value, which may decrease with increasing depth. In general, the more remote the period of primary deposition the less the probability that the main features of the present topography are similar to those which existed during that period and the less the probability of error in attributing the deposition of a rich body of primary ore to secondary processes.

Glaciation.—In comparatively late geologic time a considerable portion of North America was capped by a continental ice sheet, which removed by erosion the loose débris and the surface rock over great areas. Glaciation was most extensive in northern latitudes, but the continental glacier extended southward as far as Ohio and Missouri rivers, and smaller glaciers accumulated in the more lofty mountain ranges of the American Cordillera. Many of the ore deposits that lay in the paths of the glaciers were planed off, and the ores in their upper portions were scattered in the rocky material that was left when the ice had melted. Erratic fragments of such deposits have been carried far from their sources and have been the cause of much fruitless prospecting. Weathering does not attend erosion by ice, and at low temperatures chemical action is retarded; consequently the metals present in the portions of rocks or ore deposits that are removed are likely to be scattered by the ice rather than concentrated. The amount of rock removed by the continental ice sheet is known to be considerable, for the drift which it deposited is in many places more than 200 feet thick. It is probable that glacial erosion was in places equally great or greater. Whatever the amount of ice erosion, it appears to have been sufficient to remove the highly altered zones of sulphide deposits in most parts of northern North America.

The processes of solution are retarded in regions of low temperature. The areas in which ice erosion has been most vigorous are those in which the lower temperatures prevail today, and there is reason to suppose that the deposits in these areas were not so deeply altered before the glacial epoch as similar deposits in warmer latitudes. In Canada and in Alaska there are few large ore deposits that are clearly of secondary origin.

Glaciers do not erode their beds equally at all places. In their higher portions, where the ice is accumulating, pressures are greater, the ice is more rigid, and erosion is more vigorous. Near the margins, where the ice is melting, deposition exceeds erosion and the deposit of drift protects the surface from wear. These differences are very conspicuous in some mountainous sections of the West, where the glaciers covered only portions of the country and the processes are more clearly shown. In some of the ranges of Montana, Colorado, and Utah, where ore deposits are numerous and varied, the evidences of mountain glaciation are conspicuously preserved. At some places the mountain glaciers seem to have removed very little of the altered ore, for the secondary sulphide zones and even the oxidized ores are intact, and some of these appear to be too extensive to have been formed since the glacial epoch. In general, erosion by mountain glaciers has been localized, the maximum wear taking place near the heads of the glaciers.

Erosion by the continental glaciers also has been somewhat erratic, for great differences in the effect of the action of ice may be seen in a comparatively small area. In the Mesabi range of Minnesota the hard, fresh country rock is polished clean in places, whereas a few rods away and at but slightly lower altitudes thick bodies of cellular, powdery iron-oxide ore remain intact.

General Character of Outcrops above Sulphide Deposits.—Sulphide ores almost invariably carry iron sulphides. Although iron is readily dissolved in sulphate waters it is precipitated as hydroxide in the presence of oxygen, and the superficial zone and outcrop of a sulphide ore body are generally stained with iron. Prospectors looking for metalliferous deposits generally seek iron-stained rocks. The old Cornish term "gossan," the Spanish "colorados," and the German "eiserner Hut," applied to the outcrop, indicate iron-stained rock and generally are assumed to imply metalliferous deposits below.[1] If the sulphide ore bodies carry large proportions of iron sulphide, the outcrops will invariably carry iron. In some deposits, however, copper sulphides replace iron sulphides in the secondary sulphide zone, and the oxidation product of a chalcocite zone may

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[1] Penrose, R. A. F., Jr.: The Superficial Alteration of Ore Deposits. *Jour. Geol.*, vol. 2, pp. 298–317, 1894.

Emmons, W. H.; Outcrops of Ore Bodies, in Bain, H. F., and others: "Types of Ore Deposits," pp. 299–323, San Francisco, 1911.

show very little iron oxide. Some valuable bodies of copper ore have outcrops of light-colored kaolinized rocks that are not highly ferruginous. Some outcrops are light yellow, not rusty brown.

In recent years the discovery of rich ore bodies below brown gossan has stimulated the prospecting of iron-stained rocks in many regions. Some of the prospecting has been disappointing, for obviously a pyritic material that carries neither gold, silver, nor copper will oxidize to iron-stained rock that is chemically and mineralogically like one that may cap a deposit of copper or of precious metals.

As a general rule, the outcrop of a valuable silver deposit carries silver. The outcrops of many silver deposits are richer than the ore below, especially where horn silver (cerargyrite) forms in the gossan (see page 443). Outcrops of gold deposits also generally carry gold. If the ore is free from manganese the outcrops are usually as rich as or richer than the ore below the oxidized zone. Manganiferous gold deposits may be leached at the outcrop, but many manganiferous gold ores with a carbonate gangue are as rich near the surface as below, if not richer (see page 407). Rich copper ores may be capped by a barren gossan, but as a rule the gossan of a copper ore carries a little copper as carbonate, silicate, or oxide. Gossans of sphalerite ores may be completely leached of zinc sulphide, but calamine or smithsonite are commonly formed at the surface or not far below. Lead ores are oxidized slowly, and during oxidation insoluble products are formed, such as cerusite and anglesite. As a rule the gossan of a deposit that is rich in galena carries lead at the surface or not far below it. These relations depend on the chemical behavior of the several metals, which are discussed on pages that follow.

Conditions in the Oxidized Zone.—The oxidized zone is in the main the zone of solution. Precipitation also takes place in this zone, especially the precipitation of the oxides and hydrous oxides of iron, aluminum, manganese, and silicon. By redeposition ores of the more valuable metals also are formed in this zone. Solution generally exceeds precipitation, however, and by solution the mass is reduced and open spaces are enlarged. The increase in the size and volume of the openings renders the downward circulation comparatively free in the zone of oxidation.

Some of the metals—for example, gold—dissolve very slowly in the zone of oxidation. If the other materials in an ore deposit are taken away, however, the ore may be enriched by decrease in volume.[1]

The oxidized zone is generally above a secondary sulphide zone. As the sulphide zone is the richest part of many deposits and as the zone of oxidation is gradually descending the processes of oxidation may attack materials that are comparatively rich. In many deposits the first effect of oxidation is to convert the richer sulphides to rich oxides; consequently the lower part of the oxidized zone may be as rich as or even richer than the secondary sulphide zone.

Commonly the metals are separated in the zone of oxidation. Copper will separate from iron in cupriferous iron sulphide ore. Lead and zinc or lead and silver likewise tend to separate.

Depth of the Oxidized Zone.—The depth of the zone of oxidation and the extent of oxidation within that zone depend upon the permeability, character, and composition of the ore. Conditions differ greatly in different districts and even in different deposits in the same district. The depth of thorough oxidation is generally less than the depth of the vadose circulation, for the lowering of the zone of oxidation follows the depression of the water level. Where the ground-water level has been depressed by relatively rapid climatic change rather than by the gradual downward migration of ground water that attends the normal degradation of a country, the rate of its depression may be more rapid than that of the zone of oxidation, and in consequence the sulphide ores may be marooned in the vadose zone. In an arid country oxidation is probably slow, for it depends in a measure on the supply of oxygen-bearing waters. Thus in some districts in the Southwest the lower limit of oxidation has lagged far behind the downward-migrating water level. The depth of oxidation may vary from a few feet to 2,000 feet or more, but the greater depths are exceptional. The deepest oxidation takes place in ores containing carbonates. As a rule deposits are not thoroughly oxidized below the water level except where the water level has been elevated after oxidation.

Position and Extent of the Secondary Sulphide Zone.—The secondary sulphide zone is generally below a zone of oxidation.

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[1] Rickard, T. A.: The Formation of Bonanzas in the Upper Portions of Gold Veins, in Pošepný, Franz: "The Genesis of Ore Deposits," pp. 734–755, 1902.

It is not everywhere developed, not even in copper ores that are capped with gossan. In many deposits the transition between the oxidized and secondary sulphide zone is sharp, being essentially at the ground-water level. In such deposits the secondary ores extend downward to various distances below the water level. The vertical extent of the secondary zone differs widely in different districts. In some of the copper districts of the southern Appalachian region the chalcocite zones occupy only a few feet vertically. At Ducktown, Tenn., in all except one mine the average thickness of the secondary chalcocite zone is probably between 3 and 8 feet, but some secondary chalcopyrite is developed far below this zone. In the Encampment district, Wyoming, the vertical extent of chalcocite is at least 200 feet.

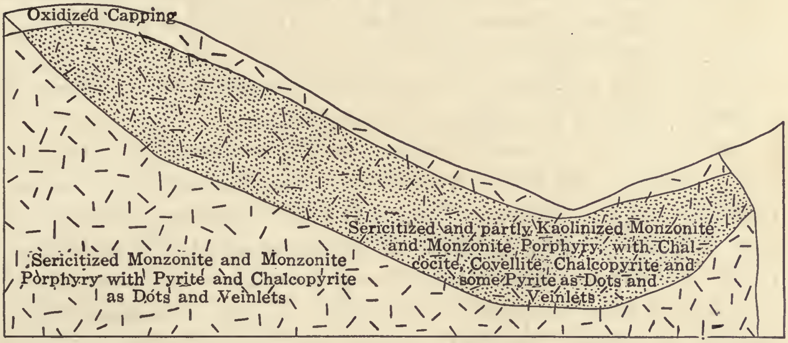

FIG. 67.—Section through disseminated copper deposit Bingham, Utah. Based on maps published by Utah Copper Company.

In the disseminated deposits in porphyry at Bingham, Utah, the zone of workable sulphides, mainly chalcocite, covellite, and chalcopyrite, has an average vertical extent of 421 feet[1] (see Fig. 67). At Globe, Ariz., in the Old Dominion mine, chalcocite has been found more than 1,200 feet below the surface and has a vertical range of at least 800 feet.

Deposits of enrichment of silver sulphide ore, at depths of 1,000 to 1,200 feet below the surface are well authenticated. Deposits of gold precipitated by descending solutions at depths more than 1,000 feet below the surface, however, are rare. In general, gold that is dissolved by surface waters is precipitated at relatively shallow depths.

No definite depth can be fixed below which processes of enrich-

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[1] Utah Copper Co. *Seventh Ann. Rept.*, Dec. 31, 1911.

ment are not effective. The maximum precipitation occurs at comparatively shallow depths, however, and there is little reason to suppose that these processes are effectively operative in the deeper part of the zone of fracture. The depths to which the metals are carried depend on local climatic conditions and on the permeability and mineral composition of the primary ore and wall rock.[1]

Relation of the Secondary Sulphide Zone to Water Level.—The ground-water level has frequently been regarded as indicating the top of the secondary sulphide zone at the time that zone was formed. The water level is not stationary but oscillates, although it tends to move downward as the major drainage channels approach grade. If the water level is comparatively high or if the lode is much fractured, and particularly if it contains large spaces, there is probably but little precipitation of the secondary sulphides above the water level. Even if precipitation should take place the sulphides precipitated would later be again exposed to oxidation and solution.

The sulphides below the water level are protected from the oxygen of the air, however, and solution of some metals is retarded if not prevented. The solution of copper sulphide, silver compounds, and gold requires an oxidizing agent. Ferrous sulphate, which is present in the reducing zone below the water level, will drive gold and silver from solution. Copper sulphide, which dissolves readily in sulphuric acid in the presence of air, is not dissolved in its absence. Hydrogen sulphide is generated by the action of acid on sulphides, and in the presence of the faintest trace of hydrogen sulphide copper sulphide is not dissolved. The solution of copper, silver, and gold would be inhibited at ground-water level or a short distance below it. Although oxygen is required for the solution of gold, silver, and copper, the sulphides of zinc and iron are dissolved at depths considerably below water level, for they are attacked by acid in the absence of an oxidizing agent.

Many deposits of secondary sulphide ore in the arid Southwest are well above the present ground-water level. The lower limits of some of these deposits have been reached by mining, and below some of them lie considerable bodies of pyrite and chalco-

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[1] Emmons, W. H.: The Mineral Composition of the Primary Ore as a Factor Determining the Vertical Range of Metals Deposited by Secondary Processes. Cong. géol. internat., 12th sess., *Compt. rend.*, pp. 261–269, 1913.

pyrite ore which have been penetrated by mine workings that encountered no standing underground water. The climate in this area has changed from humid or subhumid to arid in comparatively recent time, and it is possible that some bodies of secondary sulphide ore have been marooned by the rapid descent of the ground-water level that attended the change.

Precipitation of Sulphides above the Water Level.—In arid districts, where the water level lies very deep, the descending metal-bearing solutions may encounter a reducing environment in the vadose zone, especially in rocks that contain only minute openings, through which the water soaks downward from the surface, excluding the admission of any considerable amount of air. It would be supposed that the oxygen present in such waters and in the imprisoned air would be used up before the descending solutions encountered any zone of permanent saturation, or that the solutions might become reduced before reaching ground-water level, so that the metals could be precipitated.[1]

Textures of Secondary Ores.—Oxidized ore is generally spongy and contains numerous cavities due to solution. The iron ores formed by the superficial weathering of ferruginous igneous or sedimentary rocks are almost invariably open-textured, although in some deposits the pore space formed by the removal of valueless material is eliminated by slumping near the surface or by cementation with iron oxide at lower depths. Gossans of sulphide ores contain many openings ranging in size from minute pores to enormous caves. Stalactites, stalagmites, organ pipes, botryoidal masses, and reniform bodies are characteristic. These forms consist principally of hydrous iron oxides, subordinately of carbonates and other compounds. Similar forms are practically unknown in sulphide ores deposited by hot solutions.

The solution of primary sulphides and the precipitation of secondary sulphides may go on simultaneously, the secondary minerals replacing the primary. Pseudomorphs of chalcocite or covellite after pyrite, chalcopyrite, or zinc blende, in which the later minerals have assumed the forms of the earlier minerals, are common. Fig. 68 shows chalcocite replacing pyrite. Chalcocite, argentite, and other dark copper and silver minerals are frequently found as sooty amorphous powder coating firmer and more distinctly crystallized minerals. Commonly the sooty

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[1] Finch, J. W.: The Circulation of Underground Aqueous Solutions and Deposition of Lode Ores. Colo. Sci. Soc. *Proc.*, vol. 7, p. 238, 1904.

sulphide ores are secondary, but not invariably. Under some conditions the primary sulphides break down and form dark powdery material in an early stage of oxidation.

When some minerals have been dissolved, leaving other minerals intact, the empty spaces may be bounded by surfaces that represent former surfaces of dissolved crystals. Such spaces are commonly developed in the gossan of quartz-pyrite deposits, especially where quartz predominates and surrounds the crystals of pyrite. Galena, tungstates, and many other minerals in quartz will likewise be dissolved and leave their negative pseudomorphs. Of nearly related genesis is the texture shown by imbricating blades of quartz which join at angles that represent the cleavage of calcite. Ore of this character is shown in the oxidized zone of deposits at Bullfrog and Manhattan, Nev.; De Lamar, Idaho; Marysville, Mont.; and many other calcite-bearing deposits (see page 72). If the undissolved calcite is examined in thin section the genesis of such texture is obvious. The cleavage cracks of the calcite are filled with numerous thin plates

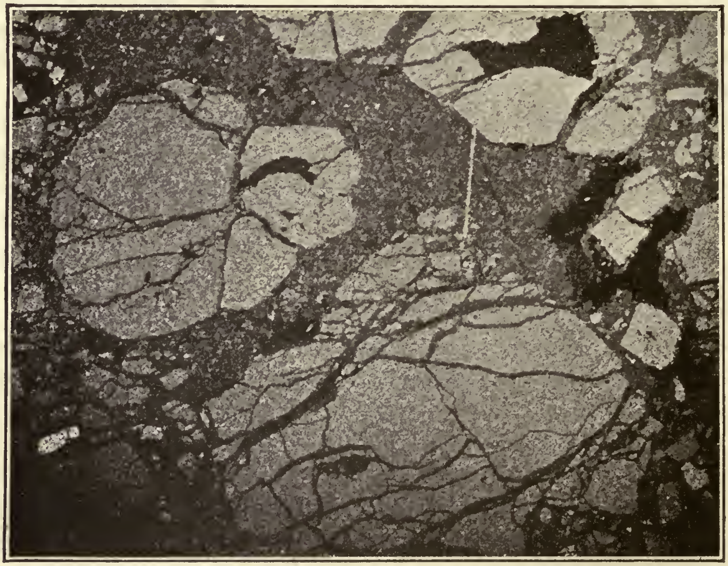

Fig. 68.—Chalcocite ore from lower limit of chalcocite zone of Ryerson mine, Morenci, Arizona. Chalcocite (dark gray) is developing by replacement in pyrite (light gray). The chalcocite is accompanied by small amounts of quartz, shreds of sericite, and kaolin. Black areas are open field. (*After Lindgren, U. S. Geol. Survey.*)

of quartz, and after the calcite has been removed the quartz plates remain. If the carbonate carries manganese, as much of it does, the quartz septa after weathering are heavily stained with black or chocolate-colored manganese oxide. Material containing solution cavities may in itself be wholly primary, but as the minerals removed have been dissolved chiefly in the oxidized zone, the negative pseudomorphs generally indicate superficial alteration.

Secondary sulphides may be developed in cleavage cracks of pyrite, galena, and other minerals, and they may show on polished surfaces a kind of indistinct network like the quartz in calcite mentioned above, the position of the thin blades being controlled by the cleavage of the older mineral.[1]

Oolitic rocks are those whose texture resembles that of fish roe. In pisolitic rocks the spheres are as large as peas, and in nodular rocks they are commonly larger, some of them much larger. The term nodular, however, is applied to spheres of all sizes. Oolitic, pisolitic, and nodular textures are formed under widely varying conditions. Marine ferruginous beds of oxides, carbonates, and silicates of iron are commonly oolitic. Weathered iron-bearing rocks and weathered aluminous rocks are commonly oolitic or pisolitic. Oolites are also formed by hot springs. Primary sulphide lode ores rarely if ever show oolitic texture, except perhaps some formed almost at the surface, where conditions were probably like those at the orifices of hot springs. Superficial alteration, however, very commonly develops nodules of various sizes (Fig. 69).

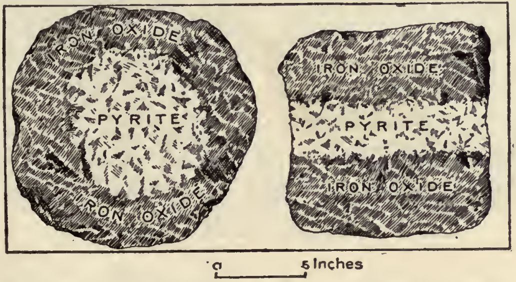

Fig. 69.—A nodule and a band of pyrite altering to limonite.

[1] Graton, L. C., and Murdoch, J.: The Sulphide Ores of Copper; Some Results of Microscopic Study. Am. Inst. Min. Eng. *Trans.*, vol. 45, pp. 26–81, 1914.

Bastin, E. S.: Metasomatism in Downward Sulphide Enrichment. *Econ. Geol.*, vol. 8, p. 60, 1913.

Much of the material that is generally termed secondary sulphide ore consists essentially of shattered and fractured primary sulphide ore, the cracks in which are filled with later sulphides (Fig. 70) or with angular fragments of the earlier sulphides crusted over with those that were introduced later. Such textures do not invariably indicate sulphide enrichment by descending solutions. Many examples show that in the course of primary mineralization the ore first deposited has been fractured and that solutions from below have deposited later sulphides in the fractures.

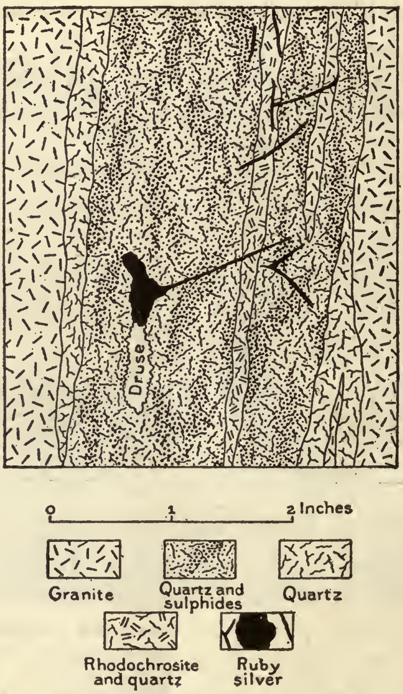

Fig. 70.—Banded ore from the South vein of the Granite-Bimetallic lode, Philipsburg, Montana. Secondary ruby silver is deposited in cross veinlets and vugs.

Pseudomorphous replacement indicates a change of physical conditions or of chemical environment. Minerals that were stable under certain conditions have been dissolved, and other minerals have simultaneously been deposited. On the other hand, fractured ore cemented by later minerals may be a result of normal and perhaps continued deposition from below. If, however, the minerals that fill the later cracks are those that are commonly formed by descending solutions, and if they do not persist in depth, the assumption that they are secondary may with considerable confidence be regarded as confirmed.

In some deposits the sulphides are intimately intergrown so that under the microscope their structure resembles that of graphic granite. Laney[1] first recognized such intergrowths in copper ores of the Virgilina district in Virginia and North Carolina (Fig. 71). Later similar intergrowths in copper ores were recognized in ores of Engel's mine, Plumas County, California;[2] at Butte, Mont.;[3] in the Bevelheimer mine, Washoe County, Nevada;[4] in the Tintic district, Utah;[5] at Mount Lyell, Tasmania

FIG. 71.—Graphic intergrowth (primary) of chalcocite (light) and bornite (dark), Wall mine, Virgilina district, Virginia and North Carolina. (*After Laney.*)

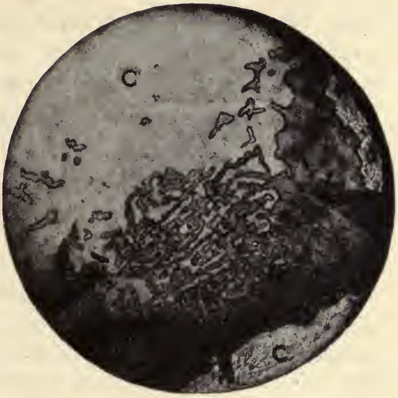

FIG. 72.—Graphic intergrowth (primary) of chalcocite (light) and bornite (dark), Mount Lyell copper mine, Tasmania. (*After Gilbert and Pogue.*)

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[1] LANEY, F. B.: The Relation of Bornite and Chalcocite in Copper Ores of the Virgilina District of North Carolina and Virginia. *Econ. Geol.*, vol. 6, pp. 399–411, 1911.

[2] ROGERS, A. F.: Secondary Sulphide Enrichment of Copper Ores, with Special Reference to Microscopic Study. *Min. and Sci. Press.*, vol. 109, p. 680, 1914.

[3] GRATON, L. C., and MURDOCH, JOSEPH: The Sulphide Ores of Copper; Some Results of Microscopic Study. Am. Inst. Min. Eng. *Trans.*, vol. 54, pp. 26–81, 1914.

[4] SEGALL, JULIUS: The Origin of Certain Crystallographic Intergrowths. *Econ. Geol.*, vol. 10, pp. 462–470, 1915.

[5] WHITEHEAD, W. L.: The Paragenesis of Certain Sulphide Intergrowths. *Econ. Geol.*, vol. 11, pp. 1–13, 1916.

(Fig. 72);[1] in the Mountain Lake mine, Big Cottonwood Canyon, Utah;[2] and at other localities. In general such structure has been regarded as characteristic of primary ores. Some geologists maintain, however, that such intergrowths may form by the replacement of one mineral by another along cleavage cracks. Segall, Whitehead, and Rogers have expressed this view.

Primary and Secondary Minerals.—In the list below are included the common ore and gangue minerals of mineral deposits and minerals that may be found in their wall rocks. Those that are primary are marked "p." These include minerals that may be formed by the replacement of other minerals at considerable depths by ascending hot waters. Minerals marked "s" may form by processes of superficial alteration and enrichment. Some minerals so marked may be formed also near the surface and at the orifices of hot springs under conditions of oxidation. Minerals that are both primary and secondary are marked "p s." Minerals that are mainly secondary but also primary are marked "s p."

MINERALS OF EPIGENETIC DEPOSITS

acmite p
actinolite p
adularia p
ægirite p
albite p
alum s
alunite p s
allanite p
amalgam s
amphibole p
analcite p
andalusite p
andradite p
anglesite s
anhydrite p
ankerite p s
anorthite p
anthophyllite p
antimony s
apatite p
aquamarine p
apophyllite p
aragonite p s
arfvedsonite p
argentite s p
arsenic s
arsenopyrite p
atacamite s
augite p
aurichalcite s
azurite s
barite p s
bastite s
bauxite s p
beryl p
biotite p
bismuth p s
bismuthinite p
bornite p s
bort p
bromyrite s
brookite p
brucite p s?
calamine s
calaverite p
calcite p s
caledonite s
calomel s
cancrinite p
cassiterite p
celestite p s?
cerusite s
cerargyrite s
chalcanthite s
chalcedony s p
chalcocite s p
chalcopyrite p s
chert p s
chlorite p s
chromite p
chrysocolla s
cinnabar p s
cobaltite p

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[1] GILBERT, C. G., and POGUE, J. E.: The Mount Lyell Copper District of Tasmania. U. S. Nat. Mus. *Proc.*, vol. 45, pp. 609–625, 1913.

[2] ROGERS, A. F.: The So-called Graphic Intergrowth of Bornite and Chalcite. *Econ. Geol.*, vol. 11, pp. 582–593, 1916.

Minerals of Epigenetic Deposits.—(*Continued*)

copper S P
corundum P
cordierite P
covellite S P
cryolite P
cuprite S
diallage P
diamond P
diopside P
dolomite P S
elæolite P
emerald P
emery P
enargite P S?
epidote P
fayalite P
fluorite P
forsterite P
franklinite P
gahnite P
galena P S
garnet P
gaylussite P
gibbsite P S
glauconite P
glaucophane P
gold (native) P S
goslarite S
greenockite S P?
graphite P
gypsum P S
halite P S
haüynite P
hematite P S
hornblende P
humite group P
hydrozincite S
ilmenite P
ilvaite P
iron (native) P
jadeite P
kalgoorlite P
kaolin S P
kyanite P
lead (native) S
leadhillite S
lepidolite P
leucite P
limonite S P
magnesite P S
magnetite P S
malachite S
manganite S
marcasite P S
melaconite S
melilite P
mercury S
microcline P
millerite S P?
molybdenite P
molybdite S
monazite P
muscovite P
nepheline P
niccolite P
noselite P
octahedrite P
olivine P
opal P S?
orpiment P S
orthoclase P
ottrelite P
pentlandite P
perofskite P
petzite P
picotite P
platinum P S?
polybasite S P?
proustite S P?
psilomelane S
pyrargyrite S P
pyrite P S
pyrolusite S
pyromorphite S
pyrophyllite P
pyroxenes P
pyrrhotite P
quartz P S
realgar P S
rhodochrosite P S?
rhodonite P
riebeckite P
ruby P
rutile P
sapphire P
scapolite P
scheelite P S?
selenite S P
sericite P
serpentine S P?
siderite P S
sillimanite P
silver (native) S P
smithsonite S
sodalite P
specularite P S?
spinel P
spodumene P
staurolite P
steatite, talc S
stephanite S P?
stibnite P
stilbite P
stromeyerite S P?
sulphur S
sylvanite P
talc S
tellurides P
tennantite P S
tenorite S
tetradymite P
tetrahedrite P S
tin (native) S
titanite P
topaz P
tourmaline P
tremolite P
tridymite P
turgite and amorphous hematite S P
turquoise S
uralite P S
valencianite P
vesuvianite P
willemite P S
witherite S
wolframite P
wollastonite P
wurtzite S
xenotime P
yttrialite P
zeolites P S
zinc blende P S
zincite P
zircon P
zoisite P

Summary of Criteria for Determination of Secondary Ores.—As secondary ores are superficial they will give out in depth; thus the problems of enrichment are vital to intelligent exploitation. Every metal behaves differently under the conditions that produce such ores. The migration of metals depends also upon the composition of the ore and gangue and upon many other factors. Yet there are certain general principles that may be applied to the investigation of all such deposits. Secondary ores may be divided into two classes—those enriched by subtraction of valueless material and consequent reduction of mass, and those enriched by precipitation or substitution of certain metals.

1. Ores that are formed by the removal of valueless material without much addition of valuable material are generally porous, the pores representing the material that has been removed; slumping near the surface and cementation below operate to eliminate pore space. Ores formed in this manner generally merge downward into low-grade protore. They usually show an evident relation to the surface and commonly also to the ground-water level; the deposits are likely to be thicker under a hilltop, where the outcrop is high and the water level farther below the outcrop, than in a valley. Ores of this character are developed on many base-leveled surfaces and may be found on plateaus or elevated regions, on surfaces that have been raised after the ores were extensively weathered. Circulation may have been controlled by structural features, and the deposits enriched by the removal of valueless material may be found fractured areas or in structural basins or in pitching troughs because circulation was active there. Ores of this class have been concentrated at the surface because the metals they contain are not readily removed by solution; in many places such metals are removed by mechanical erosion from the outcrops, and commonly they are found along streams in beds that have been formed by mechanical disintegration and deposition near by. Placer deposits and detrital sediments are frequently formed near older deposits containing metals. The minerals are those that are stable under surface conditions, the so-called end products of weathering—iron oxides, kaolin, bauxite, manganese oxides—and the stable residuals, such as magnetite, chromite, and in some deposits gold, platinum, cassiterite, and monazite.

2. Ores enriched by precipitation or substitution of certain metals may be porous and open textured, especially in the zone of oxidation; in depth cementation tends to eliminate openings.

The ores commonly show characteristic changes downward: a leached zone at and near the surface may grade into a zone of high-grade oxidized ore and this into high-grade sulphide ore, which in turn changes into low-grade sulphide ore at greater depth. Although these zones are developed in a majority of the deposits of this group, they are not everywhere developed and rapid erosion may remove one or all of them. The secondary zones are related to the topography of the time when they were formed, their tops generally lying farther below the surface, yet at higher altitudes, below hilltops than below valleys (Fig. 67). The top of the secondary sulphide zone is generally related also to the water level of the time when it was formed, but subsequent changes of the water level may obscure this relation, and in arid countries, where the water level may be very deep, secondary sulphide ores appear to have formed above and independent of the water level. Many primary ores that were formed near the surface show a relation to the topography existing when they were formed, because the maximum precipitation of the metals in the original ore body was accomplished by mingling of the hot ascending solutions with cold and perhaps oxidized meteoric waters, or by the escape of gases that had held the metals in solution. Thus a relation of the rich zone to the present topography is a more certain criterion as applied to older and more deeply eroded deposits than to younger deposits that may have been formed under topographic conditions which were perhaps similar in essential features to those now prevailing.

The metals that are concentrated by transportation and precipitation are those that go into solution and consequently those that are commonly leached from outcrops. Their deposits generally carry iron sulphides. A porous leached outcrop stained with iron suggests secondary ores below. Erosion may be so rapid, however, that the gossan is not completely leached; the valuable metals may not all be removed. Thus placers may be formed from a deposit whose gossan is only partly leached, or by rapid erosion the gossan or even the secondary sulphide zone itself may be removed, exposing the primary ore at the outcrop. Altered zones may have been tilted or faulted or covered with later igneous rocks or sedimentary beds.

The groups of minerals of the several zones are characteristic. Few minerals are exclusively primary or exclusively secondary, yet some are essentially one or the other, and an adequate study of the minerals and their relations will serve to determine the genesis of nearly all deposits. Because the heavy silicates and several other minerals characteristic of deposits formed at considerable depths are not formed by secondary processes, the mineralogic criteria are more satisfactorily applied to these deposits. Kaolin and gypsum are formed in some secondary ores by acid solutions reacting on gangue minerals or on wall rock. Other secondary ores, however, contain neither kaolin nor gypsum. The value of each common mineral as indicating genesis is discussed elsewhere.

The texture of an ore and its paragenesis may indicate its origin. The primary minerals are by definition earlier than the secondary minerals, and the latter will be found in cracks cutting the earlier ore, or replacing it along cracks. The mere fact that one association of minerals is found in cracks in an older association of minerals or that one mineral has been formed by metasomatic replacement of another is not an indication of deposition by downward-moving waters. Veins are frequently fractured after they are formed, and ascending waters may deposit minerals of different composition in the cracks. Therefore this criterion may not lead to final decision, and in considering it proper weight should be given to the mineral composition of the older and younger groups of minerals and to the relation of the ore body to other zones. From the study of a large number of deposits it is found that there are certain downward changes that may be considered standard. These standard changes, which are different for each of the metals and for each metal in different mineral associations, are discussed on pages that follow.

The vertical extent of a secondary sulphide zone, though depending somewhat on the topography, past and present, the duration of the period of erosion, the geologic history, and the environment, should show, nevertheless, a relationship to the permeability of the primary ores and to their mineral composition. In permeable primary deposits the valuable metals may be carried farther before they are precipitated than in deposits that are less permeable. But in equally permeable ores the rates at which the valuable metals are precipitated differ greatly. The secondary sulphide zone will have smaller vertical range in deposits whose primary ores act readily to precipitate the metals.

Finally, secondary ores do not contain elements that were not in the primary ores or in the country rock or in air or surface waters.

Estimates of Portions of Lodes Eroded.—Where there is reason to suppose that the primary ore was of approximately uniform composition before secondary alteration took place, it is possible to estimate the vertical extent of the portion of the deposit that has been eroded. The ore in the secondary zone generally contains valuable metals that were present in the primary ore, those that were leached from the oxidized zone above the secondary sulphide ore, and those that were leached from the portion of the deposit that has been removed—the metals that were carried downward by solutions in advance of erosion. In some deposits the material dissolved is carried away in the general circulation or is carried into fractures in the country rock and redeposited outside of the original deposits, and the loss of the original deposits should be taken into consideration.

If x equals the vertical extent in feet of the part of the lode which has been removed from above the present apex, a equals the vertical extent in feet of the leached zone, b equals the vertical extent in feet of the enriched zone, l equals the valuable metals (stated in any convenient unit, such as assay content per ton) remaining in the leached zone, e equals the valuable metals in the enriched zone, and p equals the valuable metals in the primary ore, the following formula may be applied to ascertain the number of feet removed:

$$x = \frac{a(l-p) + b(e-p)}{p}$$

This formula does not take into account the changes in mass[1] in the ore itself nor the pore space formed, and it is recognized, of course, that many other factors may modify the results; for the valuable metals in the material dissolved may not all be redeposited in the ore body, and the primary ore, before alteration and enrichment, may not have been of equal richness throughout the deposit. The estimates therefore give only a rude approximation, but one which may be used, in connection with other geologic data, as a check on conclusions regarding the minimum amount of erosion that has taken place since the primary ore was deposited.

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[1] If value can be expressed as assay content per unit volume instead of per ton, changes in mass are accounted for.

Experimental Data on Solution and Precipitation of Metals.—The oxidation of pyrite proceeds as follows:[1]

$$FeS_2 + 7O + H_2O = FeSO_4 + H_2SO_4.$$

Ferrous sulphate in the presence of air is oxidized to ferric sulphate or to ferric sulphate and ferric hydroxide:

$$6FeSO_4 + 3O + 3H_2O = 2Fe_2(SO_4)_3 + 2Fe(OH)_3.$$

The hydrolysis of ferric sulphate may first give a basic ferric sulphate,[2] but this subsequently breaks down, forming ferric hydroxide and sulphuric acid, as indicated below:

$$Fe_2(SO_4)_3 + 6H_2O = 2Fe(OH)_3 + 3H_2SO_4.$$

Ferric hydroxide on partial dehydration would give limonite:

$$4Fe(OH)_3 = 2Fe_2O_3 + 6H_2O = 2Fe_2O_3.3H_2O + 3H_2O.$$

A. N. Winchell[3] treated powdered pyrite to dripping aerated water. At the end of ten months 300 grams of pyrite had lost 0.2 gram and the solution circulating through the pyrite had gained 0.332 gram of ferric sulphate and 0.068 gram of sulphuric acid.

Grout[4] also performed these experiments, subjecting powdered pyrite to repeated drying. In a year the specimens had lost from 0.015 to 0.057 per cent. These losses are of the same order as those obtained by Winchell, namely, 0.067 per cent.

Buehler and Gottschalk[5] treated finely powdered sulphides to dripping water. Each sulphide when treated alone was dissolved slowly, but when two were treated together the action on one of them was accelerated and that on the other retarded.

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[1] ALLEN, E. T.: Sulphides of Iron and Their Genesis. *Min. and Sci. Press*, vol. 103, pp. 413–414, 1911.

GOTTSCHALK, V. H., and BUEHLER, H. A., Oxidation of Sulphides. *Econ. Geol.*, vol. 7, pp. 15–34, 1912.

[2] PENROSE, R. A. F., JR.: The Superficial Alteration of Ore Deposits. *Jour. Geol.*, vol. 2, p. 293, 1894.

BRAUNS, REINHARD: "Chemische Mineralogie," p. 368, Leipzig, 1896.

[3] WINCHELL, A. N.: The Oxidation of Pyrite. *Econ. Geol.*, vol. 2, pp. 290–294, 1907.

[4] GROUT, F. F.: The Oxidation of Pyrite. *Econ. Geol.*, vol. 3, pp. 532–534, 1908.

[5] BUEHLER, H. A., and GOTTSCHALK, V. H.: Oxidation of Sulphides. *Econ. Geol.*, vol. 5, pp. 28–35, 1910; vol. 7, pp. 15–34, 1912.

WELLS, R. C.: Electric Activity in Ore Deposits. U. S. Geol. Survey *Bull.* 548, pp. 1–78, 1914.

Sphalerite dissolved more readily in the presence of pyrite. The acid generated by the oxidation of iron sulphide was not the only factor that favored solution, for when the iron sulphide was placed on a filter above zinc sulphide the rate of solution of zinc sulphide was not greatly increased. Buehler and Gottschalk concluded that the acceleration of the reactions is due to electric currents generated by the contact of minerals of different potential. The current flows from the mineral having the higher potential, and so the one of lower potential will dissolve more rapidly, the one of higher potential being protected from oxidation and solution. The same investigators arranged several minerals in a series analogous to the electromotive series of the metals, having determined their potentials by the use of the potentiometer. The results of the experiments are shown in part below. The force generated while any two of these minerals are immersed in a solution tends to accelerate the oxidation and dissolution of that sulphide which stands lower in the series and to retard the oxidation of the one that stands higher. It is noteworthy that the experiments were made with distilled water. The potential varies with the solution, and for some salts the relations are not those indicated in the table.

POTENTIAL, IN VOLTS, OF SEVERAL SULPHIDES MEASURED IN DISTILLED WATER AGAINST COPPER WIRE

Marcasite	+0.37	Galena	+0.15
Argentite	+0.27	Chalcocite	+0.14
Chalcopyrite	+0.18 to 0.30	Metallic copper	0.00
Covellite	+0.20	Stibnite	−0.17 to 0.60
Pyrite	+0.18	Sphalerite	−0.20 to 0.40
Bornite	+0.17		

H. V. Winchell[1] placed in a sealed jar crystals of pyrite in a slightly acid solution, containing sulphur dioxide and a dilute solution of copper sulphate. At the end of 3 months films of chalcocite were deposited on the pyrite, and its copper content, which at the beginning of the experiment was 1.50 per cent., had increased to 3.60 per cent. The chalcocite coated the iron sulphide completely with glistening surfaces. In another jar, with similar reagents except sulphur dioxide, no chalcocite was deposited. Winchell suggests that sulphur dioxide is necessary for the

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[1] WINCHELL, H. V.: Synthesis of Chalcocite and Its Genesis at Butte, Mont. Geol. Soc. America *Bull.*, vol. 14, pp. 272–275, 1903.

deposition of cuprous sulphide. He infers that the cupric sulphate in solution with sulphur dioxide supplies cuprous ions for the reaction with the pyrite that supplies the sulphur for the chalcocite, the iron going into solution as ferrous salt. He found that iron was dissolved and subsequently precipitated as ferric hydroxide.

Recently Spencer[1] has discussed the possible reactions involved in chalcocite deposition and has shown that chalcocitization may result from a long series of oxidizing reactions.

In the table below the solubilities of several anhydrous sulphates are compared. Of these only the least soluble—barium, lead, and calcium sulphates—form stable minerals in ore deposits.

ANHYDROUS SULPHATES HELD IN SOLUTION IN A LITER OF WATER AT 18°C.
[After Kohlrausch]

	Grams		Grams
$BaSO_4$	0.0023	K_2SO_4	111.1000
$PbSO_4$	0.0410	Na_2SO_4	168.3000
$CaSO_4$	2.0000	$MgSO_4$	354.3000
Ag_2SO_4	5.5000	$ZnSO_4$	531.2000

Some metals are precipitated from sulphate solution by alkaline silicates. E. C. Sullivan[2] placed finely ground materials—such as orthoclase, albite, amphibole, and clay gouge—in flasks with copper sulphate, silver sulphate, and other salts. The solutions were dilute, and the precipitation of copper or silver in many of the flasks was nearly complete. Reactions of this character are probably at some places effective processes in the enrichment of ore bodies, for the essential conditions of the experiments commonly exist in nature. The neutralization of the acid solutions by the alkaline silicates permits such reactions as are favored by a neutral environment.

According to Weigel[3] the solubilities of the freshly precipitated sulphides are as follows:

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[1] SPENCER, A. C.: Chalcocite Deposition, Wash. Acad. Sci. *Jour.*, vol. 3, pp. 70–75, 1913; *Econ. Geol.*, vol. 8, pp. 621–652, 1913.

[2] SULLIVAN, E. C.: The Interaction between Minerals and Water Solutions, with Special Reference to Geologic Phenomena. U. S. Geol. Survey *Bull.* 312, pp. 37–64, 1907.

[3] WEIGEL, OSKAR: Die Löslichkeit von Schwermetallsulfiden in reinem Wasser. *Zeitschr. phys. Chemie*, vol. 58, pp. 293–300, 1907.

Solubilities of Several Sulphides Expressed as Mols per Liter $\times 10^{-6}$

MnS	71.600
ZnS	70.600
FeS	70.100
CoS	41.620
NiS	39.870
CdS	9.000
Sb_2S_3	5.200
PbS	3.600
CuS	3.510
As_2S_3	2.100
Ag_2S	0.552
Bi_2S_3	0.350
HgS	0.054

Schuermann[1] brought several metallic sulphates into contact with different metallic sulphides and established a series, the sulphides of any one of the metals of which will be precipitated at the expense of any sulphide lower in the series. This series, which he regards as showing the "relative affinity" of the heavy metals for sulphur, is mercury, silver, copper, bismuth, cadmium, antimony, tin, lead, zinc, nickel, cobalt, iron, arsenic, thallium, and manganese. Those last named have the least affinity. As pointed out by Wells, the principal results of Schuermann's experiments may be regarded as reactions establishing chemical equilibria, the salts being fixed in the order of their solubilities under the conditions of the experiments. The positions of the commoner metals in the Schuermann series agree fairly well with the solubilities of the sulphides determined by Weigel, and the metals that replace those lower in the series generally have lower solubilities than those which they replace.

Hydrogen sulphide is made in the chemical laboratory by treating artificial ferrous sulphide with acid. The generation of hydrogen sulphide is almost instantaneous. As shown by Allen, pyrrhotite is a solid solution of ferrous sulphide (FeS) and sulphur. Both pyrrhotite and zinc blende dissolve in acid with noticeable evolution of hydrogen sulphide, whereas pyrite and

[1] Schuermann, Ernst: Ueber die Verwandtschaft der Schwermetalle zum Schwefel. *Liebig's Annalen*, vol. 249, p. 326, 1888.

Emmons, S. F.: The Secondary Enrichment of Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 30, p. 212, 1901.

Weed, W. H.: The Enrichment of Gold and Silver Veins. Am. Inst. Min. Eng. *Trans.*, vol. 30, p. 428, 1901. The Affinity of Metals for Sulphur. *Eng. and Min. Jour.*, vol. 50, p. 484, 1890. Review of lecture by Watson Smith, on Schuermann's reactions. Soc. Chem. Ind. *Jour.*, vol. 11, pp. 869–871, 1892.

Zies, E. G., Allen, E. T., and Merwin, H. E.: Some Reactions Involved in Secondary Sulphide Enrichment. *Econ. Geol.*, vol. 11, pp. 407–503, 1916.

chalcopyrite are almost insoluble in sulphuric or hydrochloric acid. They are readily decomposed, however, in nitric, an oxidizing acid.

Several experiments were made by R. C. Wells to ascertain the rates at which hydrogen sulphide is generated by the action of cold dilute acid waters on sulphides of the metals. He exposed over night five minerals to 0.057 normal sulphuric acid. The resulting solutions were titrated with iodine solution to ascertain the amount of hydrogen sulphide generated, the iodine solution required being, for pyrrhotite, 28.5 cubic centimeters; for sphalerite, 1.05 cubic centimeters; for galena, 0.40 cubic centimeter; for chalcopyrite, 0.29 cubic centimeter; for pyrite, 0.28 cubic centimeter.

With equal surfaces exposed, cold dilute acid solutions set hydrogen sulphide free at least four times as rapidly from some zinc blende as from pyrite or chalcopyrite, and about twenty-five times as rapidly from pyrrhotite as from zinc blende. Zinc blende containing considerable iron sulphide will react more readily with acid than pure zinc sulphide.

Grout[1] showed that alkaline solutions react with many sulphides and give alkali sulphides that precipitate the metals from sulphate solutions. Pyrrhotite acts much more rapidly than other iron sulphides. Whether the solutions are acid or alkaline the metals will be precipitated more rapidly with pyrrhotite than with other iron sulphides.

Composition of Mine Waters.—The following tables show the results of analyses of samples of water taken from mines containing deposits of sulphide ores:

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[1] Grout, F. F.: On the Behavior of Cold Acid Sulphate Solutions of Copper, Silver, and Gold with Alkaline Extracts of Metallic Sulphides. *Econ. Geol.*, vol. 8, pp. 407–433, 1913.

Nishihara, George S.: The Rate of Reduction of Acidity of Descending Waters by Certain Ore and Gangue Minerals and Its Bearing on Secondary Sulphide Enrichment. *Econ. Geol.*, vol. 9, pp. 743–757, 1914.

ANALYSES OF MINE WATERS IN SULPHIDE DEPOSITS

(Parts per million)

WATERS OF COPPER MINES

	1	2	3	4	5
SO_4	71,053.3	2,672.0	415.8	476.8	5,064
Cl	17.7	13.0	0.7	0.4	Undet.
CO_3					
PO_4	1.5	Trace			
B_4O_7	....	Trace			
Br	....	Trace			
F	....	Trace			
SiO_2	67.4	47.7	37.0	49.9	76
K	6.8	13.1	2.7	2.2	Undet.
Na	41.7	39.6	5.2	5.5	
Li	Trace				
Ca	307.7	132.5	19.7	30.4	436
Mg	149.2	61.6	5.2	6.2	61
Al	85.2	83.5	14.5	19.1	Undet.
Mn	13.2	12.0	0.2	0.1	236
Ni	3.5	0.5			
Co	4.6				
Cu	45,633.2	59.1	28.1	11.0	1,659
Zn	411.2	852.0	2.4	2.9	Undet.
Cd	....	41.1			
Fe''	49.8	159.8	71.4	89.2	305
Fe'''			20.3	55.9	
Acidity: H_2SO_4	....	....	210.2	97.5	970

1. Mountain View mine, Butte, Montana, second level. W. F. Hillebrand, analyst. CLARKE, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 633, 1916. WEED, W. H.: Geology and and Ore Deposits of the Butte District, Montana. U. S. Geol. Survey *Prof. Paper* 74, p. 101, 1912.

2. St. Lawrence mine, Butte, Montana. W. F. Hillebrand, analyst. CLARKE, F. W.: *Op. cit.*, p. 632. WEED, W. H., *Op. cit.*, p. 101.

3. Callaway shaft, Ducktown, Tenn., at water level. R. C. Wells, analyst. EMMONS, W. H. and LANEY, F. B.: Preliminary Report on the Mineral Deposits of Ducktown, Tenn., U. S. Geol. Survey *Bull.* 470, pp. 171–172, 1911.

4. Callaway shaft, Ducktown, Tenn., 37 feet below water level. R. C. Wells, analyst. EMMONS and LANEY: *Idem.*

5. Capote mine, Cananea, Mex., 300-foot level. G. W. Hawley (chief chemist Cananea Consolidated Copper Company), analyst.

Waters of Gold and Silver Mines

	6	7	8	9
SO_4	474.00	209,100.00	60.12	2,039.51
Cl	19.00	127.60	Trace	8.16
CO_3	20.45			
SiO_2	133.40	616.00	18.00	43.80
K	53.40	....	2.41	70.00
Na	132.00	535.00	28.52	106.27
Li				
Ca	100.10	1,286.00	17.36	187.15
Mg	5.88	6,590.00	1.30	93.50
Al	1.37	9,670.00	....	3.12
Mn	....	885.10	0.25	155.58
Cu	....	147.50	....	77.05
Zn	....	....	....	49.66
Pb	....	....	....	3.44
Fe''	....	....	1.47	164.82
Fe'''	6.33	5,025.00		
H (acids)	....	2,575.00	Alk.	
CO_2	....	....	61.53	

6. C. & C. shaft (Comstock lode), Storey County, Nevada; 2,250-foot level. N. E. Wilson, analyst. Reid, J. A.: The Structure and Genesis of the Comstock Lode. Cal. Univ. Dept. Geology *Bull.* vol. 4, p. 189, 1906.

7. Central tunnel (Comstock lode), Storey County, Nevada; vadose water. N. E. Wilson, analyst. Reid, J. A., *Op. cit.*, p. 192.

8. Bachelor mine, Creede, Colorado. Iron includes some aluminum. Water is alkaline. Chase Palmer, analyst.

9. Stanley mine, Idaho Springs, Colorado. L. J. W. Jones, analyst. Jones, L. J. W.: Ferric Sulphate in Mine Waters and Its Action on Metals. Col. Sci. Soc. *Proc.*, vol. 6, for 1897–1900, p. 48.

General Character of Mine Waters.—In the table above are stated analyses of several waters from mines yielding sulphide ores of copper, gold, and silver.[1] The opening of a mine increases circulation and probably makes the waters that permeate the deposits more dilute; mine workings also permit access of air at lower levels, and this makes the waters more acid and more active solvents. It is not certain that the solutions that have enriched sulphide ores are like the waters that now traverse the deposits, but it is highly probable that they are of the same general character.

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[1] Many other analyses may be found in my paper, The Enrichment of Ore Deposits, (U. S. Geol. Survey *Bull.* 625, pp. 86–89, 1917), and in a paper by E. T. Hodge: (The Composition of Waters in Mines of Sulphide Ores). *Econ. Geol.*, vol. 10, pp. 123–139, 1915.

Sulphides exposed to air and water are changed to sulphates and to sulphuric acid. The iron minerals are the chief sources of sulphuric acid because some of them contain more sulphur than that necessary to balance iron when iron sulphate forms and because iron sulphate in the presence of oxygen forms the ferric salt, which hydrolyzes readily, giving basic ferric sulphate and ultimately limonite. Galena and zinc blende may oxidize to sulphates without liberating acid. The following equations, which represent certain stages in the reactions, illustrate this principle:

$$FeS_2 + H_2O + 7O = FeSO_4 + H_2SO_4.$$
$$CuFeS_2 + 8O = FeSO_4 + CuSO_4.$$
$$PbS + 4O = PbSO_4.$$
$$ZnS + 4O = ZnSO_4.$$

The oxidation of ferrous sulphate to ferric salt and the hydrolysis of ferric sulphate take place very readily in the presence of oxygen.

$$2FeSO_4 + H_2SO_4 + O = Fe_2(SO_4)_3 + H_2O.$$
$$6FeSO_4 + 3O + 3H_2O = 2Fe_2(SO_4)_3 + Fe_2(OH)_6.$$
$$Fe_2(SO_4)_3 + 6H_2O = 2Fe(OH)_3 + 3H_2SO_4.$$

All mine waters from sulphide deposits are sulphate solutions. They generally carry some chlorides, however, which are sparingly present in most rain water and in some wall rocks and ores. Penrose,[1] discussing the distribution of chloride ores, pointed out that the chlorides form most abundantly in undrained areas. Carbonates are present in many mine waters, especially in those that are alkaline. Nitrates are practically unknown. Hydroxides are probably present in some waters. They have not been determined in the analyses, but in several analyses their presence is suggested by the fact that the positive radicles exceed the negative radicles. Nearly all mine waters carry a little silica. Phosphates are sparingly represented in a few samples, also arsenic and antimony. Potassium and sodium are nearly always present, but as a rule sodium is the more abundant. Calcium, iron and magnesium are generally present in considerable amounts. Acid waters commonly contain aluminum and manganese. The alkalies, alkaline earths, aluminum, and manganese are dissolved by sulphuric acid, which attacks the ore and wall rock. Near the surface iron is in the ferric state. In mines of copper and zinc

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[1] Penrose, R. A. F., Jr.: The Superficial Alteration of Ore Deposits. *Jour. Geol.*, vol. 2, p. 314, 1894.

sulphides copper and zinc are generally in solution. Small amounts of gold and silver have been determined in some waters.

Changes of Mine Waters in Depth.—Waters descending from the surface through sulphide ore deposits pass through a changing chemical environment and are continually changing in composition.[1] In the oxidized zone they are oxidized waters and acid waters; when they pass below the region where oxygen is in excess their acidity and their state of oxidation change. Their reaction on sulphides produces hydrogen sulphide, and their reaction on silicates, carbonates, and other minerals decreases acidity. Iron is generally abundant in waters of pyritic ore bodies, and the degree of the oxidation of the iron is an index to the state of oxidation of the water.

The deeper waters are all ferrous sulphate waters, and many of them are alkaline. Samples 3 and 4 of the table on page 159 were taken from the same column of water standing in a shaft—one from the top and one 37 feet lower. The acidity of the deeper water is less than half that of the water at the water level. Several waters from the Capote mine, Cananea, Mexico, analyzed by George Hawley,[2] show a marked decrease of acidity with increase of depth.

Precipitates from Mine Waters under Superficial Conditions.—Many waters, after issuing from mineralized areas, deposit copious precipitates. In some mining districts the streams that carry away the underground drainage from the adits have stained their beds for great distances from the points of issue. In certain of these districts, as at Cananea, Mexico, and Bingham, Utah, the gravels above the present streams are cemented by iron oxides, showing that the processes of precipitation at the surface were operative before the mines were opened. These deposits, formed under atmospheric pressure and in the presence of oxygen, are very different from the deposits of secondary ore that are formed at depths where sulphide enrichment takes place. Few if any of them are workable for the more valuable metals.

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[1] Nishihara, G. S.: The Rate of Reduction of Acidity of Descending Waters by Certain Ore and Gangue Minerals and Its Bearing on Secondary Sulphide Enrichment. *Econ. Geol.*, vol. 9, pp. 743–757, 1914.

Hodge, E. T.: The Composition of Waters in Mines of Sulphide Ores. *Econ. Geol.*, vol. 10, pp. 123–140, 1915.

[2] See Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, p. 87, 1917.

Nearly all of them consist largely of hydrous iron oxides, hydrous aluminum compounds, and hydrous silica.

Oxidation and Solution of Metallic Sulphides.—In the presence of air the oxidation and the solution of the metallic sulphides take place simultaneously, and it is difficult to consider the two processes separately. The rate of solution depends on many factors, among them (1) the solubility of the material in water, (2) the molecular and physical structure of the material, (3) the solubility of the salts formed by oxidation, hydration, and related processes, (4) the composition, concentration, temperature, and pressure of the solutions, (5) the mineral and chemical environment, (6) the rapidity of circulation, and (7) the potential or electromotive force of the mineral compared with the electromotive force of the mineral or minerals with which it is in contact.

The following table shows the order of oxidation of some of the sulphides, according to the views of several investigators. The sulphides that are most readily attacked are placed highest in each series.

Order of Oxidation of Sulphides

1	2	3	4	5
				Pyrrhotite
			Sphalerite	Sphalerite
			Chalcocite	
Chalcocite	Chalcocite	Chalcocite	Galena	Galena
		Bornite		
	Pyrrhotite	Pyrrhotite	Pyrite	
		Chalcopyrite	Chalcopyrite	Chalcopyrite and pyrite
Pyrite	Pyrite	Pyrite	Argentite	

1. Lindgren, Waldemar: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 43, p. 180, 1905. At some places in Clifton district.
2. Emmons, W. H., and Laney, F. B.: Preliminary Report on the Mineral Deposits of Ducktown, Tenn. U. S. Geol. Survey *Bull.* 470, pp. 151–172, 1911. Above the water level.
3. Vogt, J. H. L.: Problems in the Geology of Ore Deposits, in Pošepný, Franz: "The Genesis of Ore Deposits," pp. 676–677, 1902. Order of attack of sulphides by ferric chloride.
4. Gottschalk, V. H., and Buehler, H. A.: Oxidation of Sulphides. *Econ. Geol.*, vol. 7, p. 31, 1912. Table shows relative potential of several sulphides.
5. Wells, R. C.: Table shows rate of attack of 0.057 normal solution H_2SO_4 on several sulphides (see page 158).

Chemical Changes During Oxidation of Certain Ores.—The results of the chemical changes that take place during the oxidation of sulphide deposits depend largely on the minerals that form the deposits. Some minerals disappear completely, others are partly dissolved, and some elements of still other minerals remain in the mass in new combinations. The deposits of Ducktown, Tenn. (see Fig. 73), illustrate extreme weathering. The gossans of the copper deposits have been smelted for iron, and average analyses of thousands of tons are available from furnace records. Yearly averages from the smelters of sulphide ore from the same deposits are also available. On the assumption that the average of several specific-gravity determinations of the gossan (2.2) applies to the entire mass and that the average specific gravity of the sulphide ore is 4.05, the following table has been prepared to indicate the nature of the change by which primary ore becomes gossan. Column 1*a* shows the percentage weight of the constituents of the primary sulphide ore of the Mary mine (average of all ore smelted in 1906). Column 1*b* shows its percentage weight times its specific gravity (4.05) and may be regarded as expressing the number of grams in 100 cubic centimeters of the primary ore. Column 2*a* shows the chemical composition of the gossan (average of two large shipments). Column 2*b* gives its percentage weight times its specific gravity (2.2, corresponding to 39 per cent. porosity). Column 3 shows the gain and the loss of several constituents. Losses are shown for sulphur, silica, alumina, lime, iron, zinc, copper; gains for oxygen and water. Carbon dioxide and magnesia were not determined

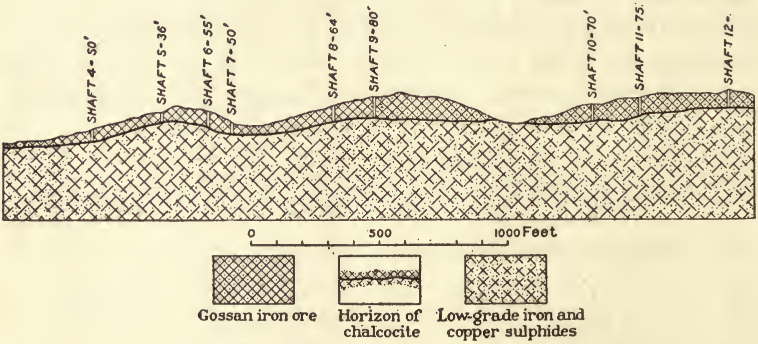

Fig. 73.—Side elevation of a part of the old Tennessee Cherokee lode, Ducktown, Tennessee, showing position of gossan iron ore, chalcocite zone, and low-grade primary copper ore.

in the analyses of gossan but were probably almost entirely carried away.

Chemical Changes by Oxidation Processes at Ducktown, Tenn.

	1*a*	1*b*	2*a*	2*b*	3
SiO_2	22.44	90.880	9.95	21.89	− 69.00
Al_2O_3	2.93	11.870	1.57	3.45	− 8.40
Fe	33.43	135.390	49.90	109.78	− 25.60
MgO	3.15	12.760	(?)	(?)	− 12.70
CaO	8.28	33.534	0.35	0.77	− 32.70
CO_2	2.85	11.540	....	....	− 11.50
S	21.23	85.980	0.65	1.43	− 84.50
MnO	0.44	1.780	....	....	....
Cu	2.45	9.920	0.86	1.89	− 8.00
Zn	2.79	11.300	....	....	− 11.30
H_2O	....	....	*a*15.40	33.88	+ 33.88
O	....	....	*a*21.38	47.04	+ 47.04
	99.99	404.954	100.06	220.13	−182.78

a H_2O and O are estimated, on the assumption that the Fe is in limonite.

The following is a close approximation to the mineral composition of the unoxidized ore:

Pyrrhotite	38.5	Calcite	6.0
Pyrite	5.1	Garnet	3.0
Chalcopyrite	7.1	Amphiboles, pyroxene, zoisite, etc	25.8
Sphalerite	4.2		
Quartz	10.3		100.0

Oxidation has changed this ore into a gossan consisting essentially of limonite with a little silica and kaolin, carrying a fraction of 1 per cent. of copper and sulphur.

Metasomatic Replacement of Primary Sulphides.—The series of Schuermann does not agree exactly with the solubilities of all the sulphides involved; but if comparatively rare metals, such as arsenic, antimony, cobalt, and bismuth, are eliminated the series is mercury, silver, copper, lead, zinc, iron—almost the same as that indicated by the molar solubilities of the sulphides as determined by Weigel.

In the processes of sulphide enrichment the primary sulphides are commonly replaced pseudomorphously by the secondary sulphides. In the diagram below the metals are placed in order of increasing solubilities of the sulphides of the metals in water, mercury sulphide being the least and iron sulphide the most soluble.

METASOMATIC REPLACEMENT OF SEVERAL SULPHIDES

[In the order of Schuermann's series]

Mercury	Silver	Copper	Lead	Zinc	Iron
Mercury					
Silver		?	On PbS	On ZnS	On FeS_2
Copper			Metasomatic	Pseudomorphic	Pseudomorphic
Lead				On ZnS	On FeS_2
Zinc					"Drives out iron"
Iron					

According to Schuermann's series it might be supposed that mercury sulphide would replace the sulphides of silver, copper, lead, zinc, and iron; that silver sulphide would replace the sulphides of copper, lead, zinc, and iron; that copper sulphide would replace the sulphides of lead, zinc, and iron; and so on. It is improbable, however, that mercury sulphide would replace extensively the more soluble sulphides of other metals, for the solutions that transport the metals are sulphate solutions, and mercury sulphate has a very low solubility. Nevertheless, secondary cinnabar is not unknown. Silver dissolves in dilute sulphuric acid solutions in the presence of ferric sulphate, and at depth its sulphide is precipitated on those of lead, zinc, and iron.

The occurrences of secondary argentite are generally described as incrustations on the primary sulphides or as veinlets cutting them. In many places secondary chalcocite contains silver which is disseminated through and doubtless contemporaneous with the copper sulphide. In view of the fact that copper sulphide is highly stable in acid solutions in the absence of an oxidizing agent, it is not remarkable that the replacement of copper sulphides by silver sulphides is not common in the deeper zones.

Copper is much more abundant in its deposits than silver, and the nature of its changes is more easily recognized. Copper sulphide replaces galena in deposits at Ducktown, Tenn., and covellite replaces galena in the San Francisco district, Utah. Copper sulphide replaces sphalerite at Morenci, Ariz.; in the San Francisco district, Utah; and at Butte, Mont. Without much doubt similar replacement is common in many mineral deposits. Examples of the pseudomorphous replacement of chalcopyrite and pyrite by copper sulphide are well established and numerous, this method being the most common mode of origin of secondary copper sulphide ores. Although there are well-authenticated examples of sulphide enrichment of lead deposits, and statements are made that lead has driven iron or zinc out of

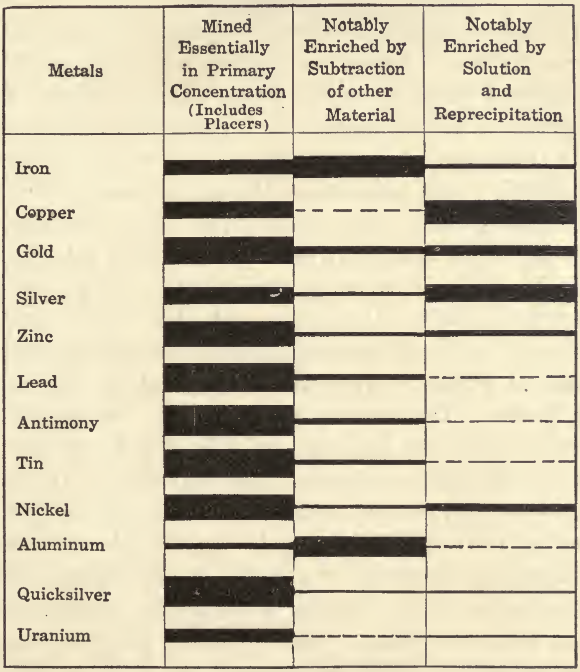

FIG. 74.—Diagram showing approximately, by width of line, an estimate of the relative importance of superficial enrichment in ore deposits and protores of several metals. Placers and all other deposits formed at places where no ore body or protore was present before are grouped in the first column with primary deposits. Broken line indicates fewer or smaller deposits than solid line; short dashes indicate fewer or smaller deposits than line with long dashes.

its sulphide combinations, lead veins afford few examples of the pseudomorphous replacement of sphalerite or pyrite. It has frequently been stated that zinc sulphide has been precipitated at the expense of iron sulphide and that zinc has driven iron out of its sulphide combination, but no examples of the pseudomorphous replacement of pyrite or marcasite by zinc blende are available. Under the usual conditions of concentration in the secondary sulphide zone a sulphide that appears to the right of the heavy line in the table on page 166 would not replace one to the left of it on the same line. Thus the copper sulphides would not be replaced by lead sulphide or zinc sulphide, and so on. Some examples, however, do not agree with the relations indicated in this series, for there are pseudomorphs of pyrite after chalcopyrite and tetrahedrite, and pseudomorphs of marcasite after galena, argentite, chalcopyrite, zinc blende, and other minerals. Probably these pseudomorphs were formed in alkaline solutions. The replacements of great economic significance are in the order of the Schuermann series. An estimate of the relative importance of enrichment in ores of several metals is shown in figure 74.

Influence of Primary Ores on the Extent of the Secondary Sulphide Zones.—The vertical extent of the secondary sulphide zone depends partly on the amount of fracturing of the primary ore body and the size, continuity, and character of the fractures. The fractures determine the course of descending waters and the rates at which the solutions descend. In their descent the metal-bearing solutions react on the walls of the watercourses, and these reactions produce changes of chemical equilibria and deposition of certain metals. These changes depend not only on the rate at which the solutions descend but also on the chemical environment through which they pass. In limestone or in calcite or siderite gangue the downward migration of copper would be delayed, at least temporarily, by the formation of carbonates, and calcite would quickly drive gold from acid solutions in which it was held dissolved as chloride.

Dilute acid waters dissolve pyrrhotite rapidly and set free hydrogen sulphide. Under similar conditions the zones of secondary ores formed from primary ores that carry abundant pyrrhotite, though generally richer, should be of smaller vertical extent than those of secondary ores formed from primary ores of pyrite and chalcopyrite that contain no pyrrhotite, for the reaction is brought near to completion more quickly. Briefly stated, the vertical extent of the secondary sulphide zones[1] should vary inversely with the rate at which the descending sulphate solutions attack the ore and gangue minerals through which they pass. In superficial alteration each metal behaves differently, its action depending on its chemical relations. These are discussed in sections treating separately the deposits of the metals.

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[1] Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, pp. 152–154, 1917.

CHAPTER XVI

OPENINGS IN ROCKS

Size of Openings.—Epigenetic deposits—that is, deposits that have been introduced by solutions into the rocks that contain them—are formed both by filling and by replacement. Briefly, they include veins of all zones, contact-metamorphic deposits, and some pegmatites. Except deposits of contact-metamorphic origin and some formed by replacement of limestone, at moderate depths, replacement deposits are generally related to easily recognized openings.

Openings may be classified with respect to their size and with respect to their origin. With respect to size, they may be placed in three groups—supercapillary, capillary, and subcapillary.[1]

Supercapillary openings are those in which water obeys the ordinary laws of hydrostatics. For water at ordinary temperatures, tubes with holes more than 0.508 millimeter in diameter or sheet openings more than 0.254 millimeter wide are supercapillary.

Capillary openings are tubes with holes less than 0.508 and greater than 0.0002 millimeter in diameter, or sheet openings between 0.254 and 0.0001 millimeter wide. In these water does not obey the ordinary laws of hydrostatics but is affected by capillary attraction. Water will not circulate so freely in such openings because of the greater friction along the walls. Hot water may move through such openings more readily than cold, however, and under pressure either hot or cold solutions may be forced through capillary openings.

Subcapillary openings include tubes with holes less than 0.0002 millimeter diameter and sheet openings less than 0.0001 millimeter wide. In these the attraction of the molecules of the solid extends across the open space. Water may enter such openings, but it tends to remain as if fixed to the walls, prohibiting further

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[1] Daniel, Alfred: "A Textbook of the Principles of Physics," p. 315, 1895.

Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, p. 135, 1904.

entrance of solutions. Circulation of solutions at ordinary temperatures through such openings is therefore very slow.

If two rocks have equal amounts of pore space—supercapillary in one and subcapillary in the other—the one with the larger openings will afford more favorable conditions for the movement of solutions. Muds, clays, shales, and rock powders, which contain exceedingly minute openings, are the great natural barriers to circulating waters, whether the waters are hot or cold. In the following genetic classification of openings the supercapillary openings and the larger capillary openings are considered chiefly, for most epigenetic deposits are related to such openings. It is noteworthy, however, that rocks containing subcapillary openings may be replaced by solutions that are under sufficient pressure at high temperature; but under most conditions such rocks tend to impede the circulation and thus to limit the size of ore bodies. Solutions that deposit ore in the minute openings in rocks generally move outward from the larger openings or "master fractures."

Origin of Openings.—With respect to their origin, openings in rocks are classified as follows:

PRIMARY OPENINGS:
- Intergranular spaces.
- Bedding planes.
- Vesicular spaces.
- Openings in pumice.
- Miarolitic cavities.
- Submicroscopic spaces.

SECONDARY OPENINGS:
- Formed by solution:
  - Caves.
  - Geodes.
  - Solution cavities in veins, etc.
- Formed by movement:
  - Shrinkage cracks due to dehydration, cooling, loss of fluids, etc.
  - Openings due to force of crystallization.
  - Openings due to the thrust of solutions.
  - Openings due to the greater earth stresses.

PRIMARY OPENINGS

Intergranular Spaces in Sedimentary Rocks.—The pore spaces in sedimentary rocks constitute a percentage of the volume of the rock ranging from less than 1 up to 20 or even more. According to Buckley,[1] the Dunnville sandstone of Wisconsin has a pore space of 28.28 per cent. Many sandstones have 10 per cent. or more. As shown by Slichter,[2] the size of the grains does not determine the amount of pore space; a fine-grained rock may be as porous as a coarse conglomerate. Fig. 75 represents a section of several balls piled so as to represent rounded sand grains. It is obvious that if this figure were to be increased or decreased in size the changes would affect similarly the solid balls and the spaces between them. The amount of space depends principally upon the assortment of grains and the system of packing. If small grains fill in the spaces between large grains, the porosity is obviously diminished. This principle is illustrated in sizing and desliming pulp for leaching in cyanide practice. The conditions for leaching are most favorable when the material is of nearly uniform size and evenly distributed. The fact that very fine material will not permit the free movement of water is not due to the absence of openings but to the small size of the openings. In rock with subcapillary openings water tends to remain fixed to the rock particles. The pore spaces of the more coarsely granular rocks like sandstone are more likely to serve as seats of ore deposition than those in fine-grained rocks like shales. Colloidal matter in shale also tends to decrease its permeability.

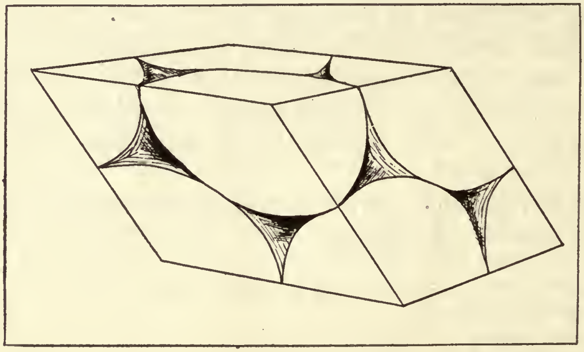

FIG. 75.—Section of balls with triangular pore spaces. (*After Slichter, U. S. Geol. Survey.*)

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[1] BUCKLEY, E. R.: Building and Ornamental Stones of Wisconsin. Wis. Geol. and Nat. Hist. Survey *Bull.* 4, pp. 225, 403, 1898.

[2] SLICHTER, C. S.: Theoretical Investigation of the Motion of Ground Waters. U. S. Geol. Survey *Nineteenth Ann. Rept.*, part 2, p. 305, 1899.

In the Keweenaw copper district of the Lake Superior region, conglomerates carry valuable ore bodies. Sandstones in many districts are impregnated with metallic sulphides or with carbonates.

Bedding Planes.—Bedding planes are due to the assortment or sizing of material during transportation and deposition. On account of the assortment of grains there may be also different arrangements of the pore spaces in the different beds.[1] Consequently, even in a nearly homogeneous rock the different beds commonly have different degrees of permeability. Water moving along the beds may follow the most permeable layer, but water moving across them must traverse also the most impermeable layers. Solutions will therefore pass along beds more readily than across them. Because of the greater permeability of certain layers, many ore deposits that obviously have been introduced after the beds containing them were laid down are found below beds of shale or beds of material somewhat more aluminous than the associated beds. Deposition may take place along bedding planes also because certain layers are more readily replaced than others. A pure limestone will commonly be more readily replaced than a clayey limestone, because it is more soluble and also more permeable. Bedding planes, especially in tilted rocks, are likely to be fissured and faulted because they are planes of easy separation. The terms "bed vein" and "bedded vein" are sometimes used synonymously with bedding-plane deposit, but the use of this term as applied to deposits that are later than the containing rocks is not to be encouraged. Examples of bedding-plane deposits are cited on page 197.

Vesicular Spaces.—Magmas generally contain included fluids. When the magmas are erupted and flow out upon the surface, pressure is relieved and the fluids expand and escape as gases. If they expand when the lavas are in a sticky or viscous condition, and near the point of solidification, the openings due to expansion are preserved. In the diabases of the Keweenaw region of Michigan (see page 395) such openings contain ore and gangue minerals in large quantities, but in many regions vesicular spaces in lavas are not especially favorable places for ore deposits. The openings due to expanded gases in lavas, unlike the pores in sandstone, are generally not connected and therefore do not offer continuous passages to solutions. That waters penetrate them

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[1] King, F. H.: Principles and Conditions of the Movements of Ground Water. U. S. Geol Survey *Nineteenth Ann. Rept.*, part 2, p. 135, 1899.

in some places, however, is shown by the abundance of amygdaloidal matter which is found in the vesicles.

Openings in Pumice.—Pumices are lavas that contain very large amounts of pore space. The openings are formed in the same manner as vesicles but are generally smaller and much more numerous. Siliceous lavas, such as rhyolites and other acidic rocks, are more viscous than basic lavas, such as basalt or diabase. Rock froth is more generally formed with siliceous material, although both acidic and basic lavas are commonly vesicular. Open spaces in a pumice are not continuous, and the water circulation in them is slow. Fragments of pumice placed in water may float for days before the spaces are filled and the waterlogged fragments sink. Metalliferous deposits in pumice are rare.

Miarolitic Cavities.—Some igneous rocks and some pegmatites contain small openings which are believed to be spaces formerly occupied by fluids of the rock magma that were unable to escape during the solidification of the rock. Such openings, called miarolitic, are present in rocks that solidified under pressure and are unlike vesicles, although both are due to imprisoned fluids. The miarolitic cavities are in general not so nearly spherical as vesicular openings, although their dimensions are more nearly equal than those of spaces formed by movement. The walls of miarolitic cavities are usually rough, because they are lined by crystals of the rock. Miarolitic cavities are not known to be seats of deposition of metalliferous ores of economic importance. In many pegmatites they contain gems and other minerals, especially minerals which, because they contain elements of the so-called mineralizers, boron, fluorine, lithium, etc., and because they generally line the cavities, are presumed to have been formed at a late stage of crystallization.

Submicroscopic Spaces.—The denser rocks, which appear solid, contain nevertheless small amounts of pore space. A granite, which under the microscope has no visible openings, will absorb a small amount of water in the cold. At high temperatures the speed of absorption is increased, and under pressure hot water may be forced through the denser rocks. Many minerals and rocks when boiled in dye are colored. The relations of hydrothermally altered rocks to fissures suggest, however, that the rate of transfer of material by solutions in such dense rocks is very slow, for as a rule the hydrothermal alteration does not extend far away from visible openings. The restriction of such alteration to the walls near the major channels is more noticeable in rocks that have been altered at greater depths, where the rocks were fractured under greater pressure.

SECONDARY OPENINGS

Openings Formed by Solution.—In soluble rocks like limestones and dolomites large openings may be formed by solution and by removal of rock matter. Solution usually proceeds by enlarging smaller openings, such as joints, bedding planes, or fissures. These openings may become the principal drainage channels of the country, and the solution cavities along them may be developed on an enormous scale. As a rule solution is more active above the water level, but large cavities have been found considerably below the present water level, especially where subsequent to solution there have been changes in the drainage or climate and in the position of the water level.

Before the development of the theory of replacement large solution cavities, such as limestone caves, were assumed to play an important part in the genesis of many ore deposits, but most investigators at present are inclined to minimize their importance. It is believed, however, that many of the zinc deposits of southwestern Missouri[1] fill ancient limestone caverns that were formed during a period of erosion between Mississippian and Pennsylvanian time.

The ore of veins is frequently dissolved out along fractures. Deposits which are assumed to have replaced solid rock may contain solution cavities of considerable size, especially in soluble material. Geodes in limestone and some open spaces in veins are clearly due to solution.

Openings Due to Shrinkage.—Shrinkage may be caused by dolomitization, dehydration, cooling, and other processes. If a fairly pure limestone is changed to dolomite without addition of carbon dioxide a shrinkage of about 12 per cent. takes place.

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[1] SIEBENTHAL, C. E.: Origin of the Zinc and Lead Deposits of the Joplin Region. U. S. Geol. Survey *Bull.* 606, p. 28, 1915.

SMITH, W. S. T., and SIEBENTHAL, C. E.: U. S. Geol. Survey *Geol. Atlas*, Joplin district folio (No. 148), p. 11, 1907.

BAIN, H. F., and VAN HISE, C. R.: Preliminary Report on the Lead and Zinc Deposits of the Ozark Region. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 2, pp. 23–228, 1901.

The porosity of some dolomites is assumed to be due to shrinkage. Cracks due to shrinkage in drying are common. Cooling cracks are formed soon after the solidification of igneous rocks, before they have cooled to the temperature of the surrounding rocks. The planes separating the columns of some basalt dikes and the irregular fractures in some granites and other rocks are commonly attributed to cooling. In observed examples where such partings are clearly due to cooling the individual openings are not continuous, but they either form small patterns like the hexagonally arranged cracks in some basalts or are irregular.

Magmas are known to be intruded into the upper part of the earth's crust at high temperatures, but where they are heavily charged with water and other fluids they remain liquid until they have lost a considerable part of their heat. The temperature of solidification may reasonably be estimated as high as 600°C. or higher, and in cooling to the temperature of the surrounding rocks they probably lose heat equivalent to 500°C. or more. Some experiments indicate that for every degree which a rock cools it will shrink about 0.002 per cent. of its volume.[1] At that rate, in cooling 500°C. it would shrink 1.0 per cent. If all spaces due to such shrinkage were expressed as parallel fissures, then an area a mile wide should have a sum of open spaces equivalent to 1 per cent. of a mile, or about 52 feet measured at right angles to such fissures. It thus appears that shrinkage during cooling is competent to form openings the sum total of which would be comparable in size to the fissures filled in an area where ore veins are rather closely spaced. It is uncertain, however, whether many metallized fractures of common types have formed by shrinkage. In most districts, although great bodies of rock have shrunk from cooling, the mineralized fractures are found only in restricted areas. Fractures may be formed by the settling of large bodies of rock due to cooling and shrinkage of rocks below them.

Openings Due to the Force of Crystallization.—The force which crystallizing matter exerts on the containing walls has been assumed to be sufficient to push the walls apart. If this force so operates it would be supposed that a metalliferous solution, having once gained entrance to a fissure, however narrow, could enlarge the fissure while it was being filled. This process

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[1] Chamberlin, T. C., and Salisbury, R. D.: "Geology," vol. 1, p. 573, 1909.

does not produce open spaces but is assumed to widen those already formed. Becker and Day[1] performed experiments to ascertain the strength of such a force and found it to be of the same order as the crushing strength of crystals. They say: "It is manifest that we here have to deal with a force of great geological importance. If quartz, during crystallization, exerts a pressure on the sides of a vein which is of the same order of magnitude which it offers to crushing, then this force is also of the same order of magnitude as the resistance of the wall rocks, and it thus becomes possible that * * * veins have actually been widened to an important extent, perhaps as much as 100 per cent. or even more, by pressure due to this cause." Laney,[2] recognizes this force as a possible factor in the formation of the spaces that are occupied by the gold veins of Gold Hill, N. C., and the cracks in pyrite in which chalcopyrite forms thin seams. Dunn[3] considers the force of crystallization as an agent that has operated in expanding the openings of quartz-filled reefs of Bendigo, Victoria. The hypothesis appears, however, to be of limited application, if not untenable for many deposits. Very commonly fissure veins show numerous vugs, and it is improbable that crystals, where they could grow freely into open spaces, would thrust aside great masses of rock. Moreover, the crystals themselves are generally not distorted. They do not show that their own growth was affected by such enormous pressures as are demanded by this hypothesis.

Openings Due to Pressure of Solutions.—In his discussion of the origin of certain small lenticular bodies of quartz ore in the schists of the southern Appalachians, Graton[4] has suggested that the metalliferous solutions themselves were under heavy pressure, sufficient to push the rocks apart along their cleavage planes, making the openings while they filled them, after the manner of igneous injections (see page 54).

Openings Due to the Greater Stresses.—The earth is losing heat and shrinking. The exterior or shell receives heat from the

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[1] Becker, G. F., and Day, A. L.: The Linear Force of Growing Crystals. Wash. Acad. Sci. *Proc.*, vol. 7, pp. 282–288, 1905.

[2] Laney, F. B.: The Gold Hill Mining District. North Carolina Geol. and Econ. Survey *Bull.* 21, p. 91, 1910.

[3] Dunn, E. J.: Report on the Bendigo Gold Field, Victoria, p. 25, Dept. of Mines, 1896.

[4] Graton, L. C.: Reconnaissance of Some Gold and Tin Deposits of the Southern Appalachians. U. S. Geol. Survey *Bull.* 293, p. 60, 1906.

interior and radiates it but probably remains at approximately the same average temperature through long periods. The loss of heat causes the interior to shrink more rapidly than the shell, which is then too large to fit the core. The shell is not strong enough to bear its own weight. Consequently it is a failing structure which is pulled downward by gravity and is wrinkled here and there, thus becoming smaller. There are probably also causes other than the loss of heat for the shrinkage of the interior.[1]

As a result of this failure of the shell, rocks are folded and mountain chains are formed. These are commonly ascribed to compressive stresses, because they are formed in the main by compression and shortening of the earth's crust. Obviously they are due to the pull or tension of gravity acting along the radii of the earth, but this force is resolved into various forces which act in many directions, and those along which movement takes place most readily are mainly at right angles to the radii, or approximately along the great circles of the earth, which are shortened or compressed. When magmas are thrust into the crust or extravasated upon the earth, the rocks above the places they previously occupied tend to settle, and such readjustment sets up stresses of various kinds. Relief of stress may be accomplished by fracturing.

The larger earth fractures are commonly referred to three classes—compressional fractures, tensional fractures, and torsional fractures.

Compressional Fractures.—Many fractures filled with ore have been formed by the relief of compressive stresses. In the classic experiment of Daubrée[2] a brittle block was subjected to pressure applied at its end. The block when viewed from the side shows two sets of fissures approximately at right angles to each other, making angles of about 45° with the direction of pressure (see Fig. 76). In some mining districts there are two groups of nearly parallel intersecting fissures, and from analogy with Daubrée's experiment these are assumed to have resulted from compressive stresses.

In this experiment it was possible for movement outward to

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[1] Chamberlin, T. C., and Salisbury, R. D.: "Geology," vol. 1, p. 548, 1909.

[2] Daubrée, A.: "Études synthétiques de géologie expérimentale," p. 318, 1879.

Becker, G. F.: Finite Homogeneous Strain, Flow, and Rupture of Rocks. Geol. Soc. America *Bull.*, vol. 4, p. 13, 1892.

take place in all directions except vertically. Consequently several coördinate systems of fractures are shown on the four free sides. But if the block had been buttressed on one, two, or three sides, then movement would have been restricted and there would be a smaller number of systems.

When a block of rock near the surface of the earth is deformed by compression, it is free to move upward. In that direction only gravity opposes movement due to lateral thrust; in other directions it is buttressed by the surrounding rocks. If the mass can move in one direction only, the number of fracture systems is obviously diminished and stresses may be relieved by one system only. In a large number of mining districts there are many veins that are rudely parallel both on strike and dip. In general, however, the surrounding rocks and the compressed mass itself are heterogeneous and of different strengths. The fracture systems are not all developed with regular patterns of any kind, although a tendency to parallelism or coördination is common in many districts.

Under compressive stress fractures will develop along planes of maximum shear[1] which are inclined to the direction of maximum stress. In Daubrée's experiment the shear planes are inclined at about 45° to the direction of stress. This experiment illustrates nonrotational strain.[2] Rotational strains are those in which the planes of strain are rotated during deformation. The planes of shear are not grouped symmetrically with reference to the direction of stress but are rotated and may intersect it at very small angles.

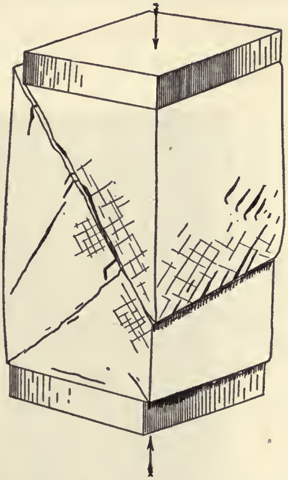

FIG. 76.—Block of material deformed by pressure applied at end. (*After Daubrée.*)

The experiment of Daubrée was made on a body of homogeneous material. Rocks as a rule are not homogeneous but are bedded, sheeted, or jointed in varying degrees. Experiments made by W. B. Lang show the effect of the grain in deformation of

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[1] LEITH, C. K.: "Structural Geology," p. 16, 1913.

[2] HOSKINS, L. M.: Flow and Fracture of Rocks as Related to Structure. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 1, p. 845, 1896.

a block of wood that had been soaked in hot water. Small openings developed along planes of maximum shear (see Fig. 77). Changes of this character may illustrate those resulting from the deformation of tough rocks, such as some schists and some slates. Fig. 78 shows the effect of pressure on a column of dry oak. Fractures are developed in rudely parallel systems, and the longer axes of each system lie at about 45° to the direction of pressure. Single systems made up of many short parallel fractures like the two systems shown in Fig. 78 are commonly developed in a testing machine where wooden blocks deformed by pressure are arranged so that one end of the block is free to move, as is the case during rotational strains.

Fig. 77.—Block of oak deformed by applying pressure in direction of arrows. (*After Lang.*)

Fig. 78.—Column of oak deformed by applying pressure in direction of arrows. (*After Lang.*)

Tensional Fractures.—Rupture by tension in homogeneous bodies takes place in planes that lie approximately at right angles to the direction of the force. Of the greater stresses acting parallel to the earth's surface, or along the great circles of the earth, the dominant ones are compressional rather than tensional, and the larger number of ore veins are probably related to the fractures resulting from compression. Some fissures, however, are clearly due to tension that results from compressional stress. Thus when brittle rocks are compressed into folds, fractures may be formed across the bedding, especially near the axes of the folds (see Fig. 79). The crest of an anticline may be stretched as a result of compression of its limbs. At the crests of folds rocks may separate also along the beds, leaving open spaces which may be filled with ore (see Fig. 80). Some bedding-plane deposits are either confined to or greatly enlarged at the crests of anticlines. Such places are favorable for ore deposition, doubtless because the openings formed during deformation supply passages for solutions. Many anticlinal deposits and saddles (see page 201) are formed by the replacement of soluble calcareous rocks, and it is probable that the fracturing during deformation has favored the entrance of the replacing solutions at the crests of the folds. Tensional fractures may be formed also by the drying out of sedimentary rocks, by the shrinkage of cooling igneous bodies (page 175), and by the settling of blocks that may attend igneous activities.[1] Tensional stresses may operate when rocks are deformed near the surface, where pressures are comparatively low.

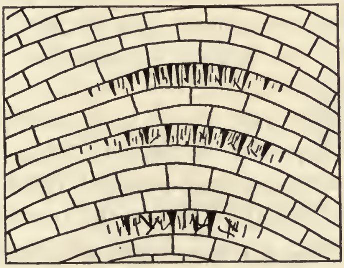

Fig. 79.—Diagram showing brittle beds fractured at and near the axis of an anticline.

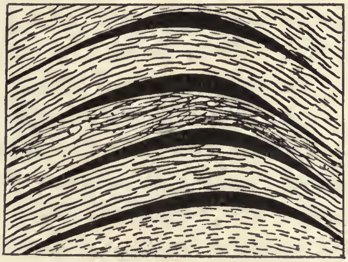

Fig. 80.—Diagram showing spaces developed at and near axis of an anticline.

A study of the thickness of the earth's shell involved in mountain folds[2] and in faulted regions shows that the deformed mass probably extends only a few miles below the surface. T. C. Chamberlin[3] suggests that there is probably a "horizon of shear" a few miles below the surface which plays a very important part in deformation. This shear zone he considers the basal

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[1] Spurr, J. E.: The Relation of Ore Deposition to Faults. *Econ. Geol.*, vol. 11, pp. 601–622, 1916.

[2] Chamberlin, R. T.: Appalachian Folds of Central Pennsylvania. *Jour. Geol.*, vol. 18, pp. 228–251, 1910.

[3] Chamberlin, T. C.: The Fault Problem. *Econ. Geol.*, vol. 2, p. 598, 1907.

plane of the greater fault blocks—a plane in which the shell shears over the subshell. The huge thrust faults like those recognized in Alberta and Montana may be the outcropping edges of the great shear plane that exists at the base of the shell and that is exposed only in a few regions.

Continents, plateaus, or mountain ranges may be elevated by compression of the earth's shell. They are surrounded by lower regions: the ocean basins, for example, are several miles below the continental platforms. At the bases of continental bodies there are unbalanced pressures of 10,000 to 30,000 pounds to the square inch. Chamberlin postulates slow movements of rocks to lower regions along the great shear zone. This continental creep or creep of any elevated region toward lower regions he compares to the movement of a glacier over the earth's surface. Thus tension cracks may be formed comparable to the crevasses that are formed in glaciers.[1]

Thrust faulting and folding, which usually result in shortening the earth's crust, are followed by a period of creep faulting or normal faulting, which usually results in extending the earth's crust. This hypohesis suggests an explanation for the conclusion reached by many observers that normal faults are more numerous than other faults.

Torsional Fractures.—To illustrate the effect of torsion, experiments have been made[2] in which a plate of glass covered with a brittle wax was held firmly at one end and twisted. Figure 81 shows the character of the fractures resulting from such stresses. They follow two general directions, cross at nearly the same angles, and are inclined about 45° with the axis of torsion. Some cracks are very short; others extend across the plate. In general, the short cracks stop at longer cracks. They are not displaced by the longer cracks, but are obviously contemporaneous with them. Some of the longer cracks radiate from points, making fan-like patterns.

Becker, Leith[3] and Lindgren[4] regard torsional cracks as due to

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[1] Chamberlin, T. C.: *Op. cit.*, p. 712.

[2] Daubrée, A.: "Études synthétiques de géologie expérimentale," p. 310, 1879.

Becker, G. F.: The Torsional Theory of Joints. Am. Inst. Min. Eng. *Trans.*, vol. 24, p. 130, 1894. Finite Homogeneous Strain, Flow, and Rupture of Rocks. Geol. Soc. America *Bull.*, vol. 4, p. 48, 1893.

[3] Leith, C. K.: "Structural Geology," p. 15, 1913.

[4] Lindgren, Waldemar: "Mineral Deposits," p. 135, 1913.

tension rather than compression. In general they are not considered important seats of ore deposition. In some districts, however, the master fractures are joined at small angles by

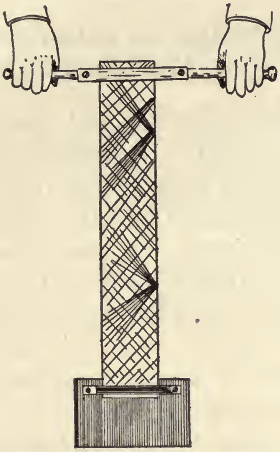

FIG. 81.—Sketch showing effect of torsion on glass plate. Lower end was held fast to block and upper end was twisted. (*After Daubrée.*)

many branching fractures. Possibly torsional stresses have modified some vein patterns formed principally by compressional stresses.

CHAPTER XVII

STRUCTURAL FEATURES OF OPENINGS IN ROCKS AND OF EPIGENETIC DEPOSITS

Ore deposits, both syngenetic and epigenetic, are commonly classified according to form. Syngenetic deposits are generally of simple form except in folded rocks, where they have participated in all the deformation affecting the contemporaneous or later rocks with which they are associated. Of the terms describing forms that are defined below, all are applied to epigenetic deposits; a few, such as "saddle" and "trough," may be applied also to syngenetic deposits; some irregular, rudely equidimensional deposits formed by magmatic segregation may be termed "chambers." Some writers use the term "lode" to describe a sedimentary ore bed that is rudely tabular and not horizontal, but this usage is to be discouraged. "Ore bed" is a better term; "seam" is applied to the sedimentary iron-ore beds of Birmingham, Ala., and similar deposits.

The origin of openings is briefly discussed on preceding pages. Certain definitions that are convenient for description are given below.

Fissure.—A fissure is an opening or parting in the earth's crust that is due to movement. It may be a mere crack with no visible space, like a crack in a pane of glass that does not extend across it, or it may present a wide open space. The movement may all be across or nearly at right angles to the crack, and the elasticity of the broken material may practically close the opening. If there has been movement parallel to the plane of the fissure it is termed a fault fissure.[1] Joints are essentially small fissures.

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[1] The use of the term "fault fissure" is not uniform. Many apply it to fissures which contain gouge or fragments rounded by abrasion or whose walls are striated or grooved. On the other hand, some investigators apply the term only to those fissures along which beds, veins, or other bodies are cut off. In surface mapping this practice is common; in underground mapping most investigators use the term "fault" to describe fissures along which there is any evidence of tangential movement, such as slickensides or gouge, even where no geologic bodies are observed to be displaced.

Fissures range in length from inches to miles. Some faults have been traced for many miles, and some fault systems for scores or hundreds of miles; but few single mineralized fissures are known to be more than 5 or 6 miles long. The Comstock lode is about 3 miles long; some of the veins near Telluride, Colo., are 3 or 4 miles long; the Amethyst vein, at Creede, Colo., is workable for about 2 miles. Many fissures are more than a mile long. In actual practice the exact points at which the larger fissures end are seldom found except where they join other fissures or faults; but it is common to find the terminations of ore shoots in fissures, and also of the mineralized parts of fissures that are of too low grade to work.

Many fissure veins have been explored to depths of half a mile or more, and there is much evidence that some of them when formed extended more than a mile below the surface.

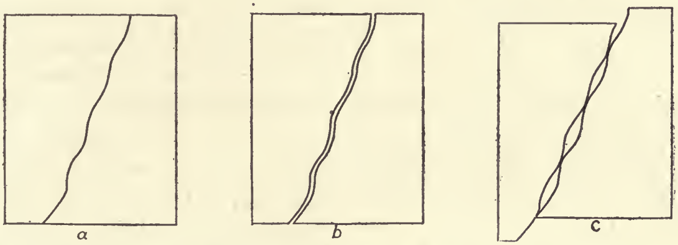

Fig. 82.—*a*, Undulating fissure; *b*, undulating fissure after movement at right angles to its plane; *c*, undulating fissure showing lenticular openings developed by movement along plane.

Many fissures are narrow. There is evidence that many veins have been formed mainly by replacement; the original spaces along the fissures of such deposits were narrower than the veins, and perhaps some were only thin openings. Many wide veins were formed, at least in part, by replacement. Long, wide spaces are probably rare, especially at great depths, yet in some veins there must have been much open space, for the vugs or unfilled portions that remain in them are numerous and widely separated.

Movements along an undulating fissure may yield open spaces (see Fig. 82). By mapping both walls of the original opening the amount of movement may sometimes be determined. The fact that few veins are of even approximately uniform width indicates irregularities of open spaces in zones of fracturing. A great many veins occupy zones of shattering, sheeting, crushing, or horse-tail structure, along which openings have been filled and shattered rock replaced.

The importance of original fractures, however narrow, is obvious: replacement is generally confined to the wall rock near the openings; the force of crystallization acts where there are original openings; the thrust of solutions is in cracks already formed.

Vein.—A vein[1] is a tabular mineral mass occupying or closely associated with a fracture or set of fractures formed by deposition from solutions either by filling fissures and pores in the wall rock, or by replacement of the wall rock, or by both filling and replacement. The term "true fissure vein," as generally used, is intended to imply persistence in depth. It is a favorite term with some promoters of mining companies. As any vein is obviously "true" the term has little real significance and is redundant.

Fault Fissure Vein.—A fault fissure vein is a vein that occupies a fault fissure. Many fault fissures with indeterminate throw show evidence of movement of the rocks along the fissure, such as slickensides or triturated rock.. Many investigators, however, apply the term "fault fissure" only to those veins along which it is possible to prove displacement.

Lode.—A lode is a tabular ore body, an ore body with one short and two long dimensions. The term may be applied to veins, deposits in sheeted or fracture zones, or replaced beds. It is applied also to deposits filling a number of thin, closely spaced, anastomosing fissures. The term generally carries the idea of a linear outcrop, though it is sometimes applied to ore bodies that do not crop out.

Reef.—In Australia and some other British colonies the term "reef" is used synonymously with "vein." In general it is applied to a vein that projects above the surface, but in Australia it is applied to some ore bodies that do not outcrop. The "saddle reef" is a deposit at the crest of an anticline.

Ledge.—The term "ledge" is sometimes used as a synonym of "vein." Like "reef," it may designate a lode projecting above the surface. As defined by Ransome,[2] it is applied to

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[1] Lindgren, Waldemar: Metasomatic Processes in Fissure Veins. Am. Inst. Min. Eng. *Trans.*, vol. 30, p. 580, 1901.

[2] Ransome, F. L.: The Geology and Ore Deposits of Goldfield, Nevada. U. S. Geol. Survey *Prof. Paper* 66, p. 150, 1909.

irregular masses of altered and mineralized rock, traversed by multitudes of small, irregularly intersecting fractures that pass locally into areas of thorough brecciation. Although the word is suggested by the outcrop of such material, it is applied to mineralized rocks at all depths.

Ladder Vein.—A ladder vein is a fractured zone in which there are cross fractures more or less regularly spaced. The type is not common and generally is found in dikes or earlier veins that are fractured. Quartz stringers with a ladder-like arrangement locally cut the Standard-Mammoth lode of the Coeur d'Alene district, Idaho[1] (see Fig. 83). The Morning Star dike, Woods Point, Victoria,[2] which is mineralized by cross fracture, is a ladder vein.

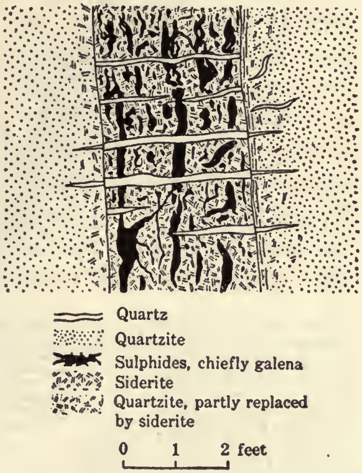

Fig. 83.—Generalized sketch of part of Standard-Mammoth lode, Coeur d'Alene district, Idaho, showing lode cross barred with small veins of barren quartz. (*After Ransome, U. S. Geol. Survey.*)

Fractured Zone.—A fractured zone is a mass of rock cut by a large number of small irregular fractures, the mass as a whole being more or less tabular (see Fig. 84). The fissures ordinarily are filled with veinlets very closely spaced, and the country rock is replaced with ore. Such a mass, if workable, is commonly mined as a unit.

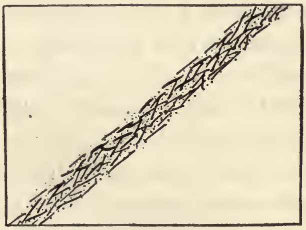

Fig. 84.—Fractured zone.

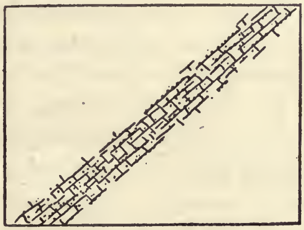

Fig. 85.—Reticulated vein.

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[1] Ransome, F. L., and Calkins, F. C.: Geology and Ore Deposits of the Coeur d'Alene District, Idaho. U. S. Geol. Survey *Prof. Paper* 62, p. 128, 1908.

[2] Lindgren, Waldemar: "Mineral Deposits," p. 134, 1913.

Reticulated Vein.—A reticulated vein (Fig. 85) is a fractured zone in which the fissures are rudely coördinate, forming a net-like pattern.

Disseminated Deposit.—In some ore bodies the metallic minerals occur as thin, closely spaced seams or veinlets, and the rock between carries also numerous "shots" and seams of ore, the whole mass being workable where mining and milling costs are sufficiently low. These are commonly termed disseminated deposits (Fig. 86). Examples include the "porphyry" copper deposits of Bingham, Utah; Ely, Nev.; Morenci, Silverbell, and Ajo, Ariz.; Santa Rita and the Burro Mountains, N. Mex.; Cananea, Mex., and many others. The ores of Miami and Ray, Ariz., are disseminated in schist.

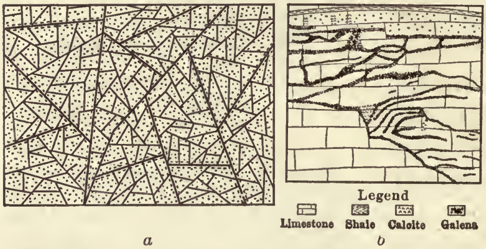

FIG. 86.—*a*, Disseminated deposit in igneous rock; *b*, disseminated deposit in limestone. (*After Buckley.*)

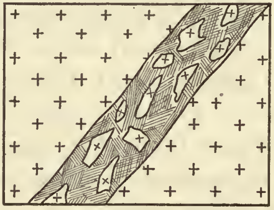

FIG. 87.—Breccia vein.

Stockwork.—A stockwork is a mass of rock cut by a large number of intersecting reticulated or irregular veins or veinlets. The country rock is generally impregnated with or replaced by "shots" of ore, so that the whole deposit may be workable. The stockwork differs from the reticulated vein or fractured zone in that the mass as a whole is generally less definitely tabular. The ore in a stockwork is usually disseminated ore.

Breccia Vein.—In a breccia vein the vein matter fills the spaces around numerous fragments of wall rock inclosed within the walls of the fissure (see Fig. 87). The proportion of filling to inclosed country rock is generally greater in a breccia vein than in a disseminated deposit, sheeted zone, fractured zone, or reticulated vein. Some of the veins of Telluride, Colo.,[1] are breccia veins.

Sheeted Zone.—A sheeted zone (Fig. 88) is made up of a number of closely spaced parallel fissures. These may be filled with

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[1] PURINGTON, C. W.: A Preliminary Report on the Mining Industries of the Telluride Quadrangle, Colorado. U. S. Geol. Survey *Eighteenth Ann. Rept.*, part 3, p. 771, 1898.

ore, and the country rock between them may be partly replaced. If the veins are of fair size and the intervening bodies of country rock are relatively small, the sheeted zone is commonly termed a compound vein.

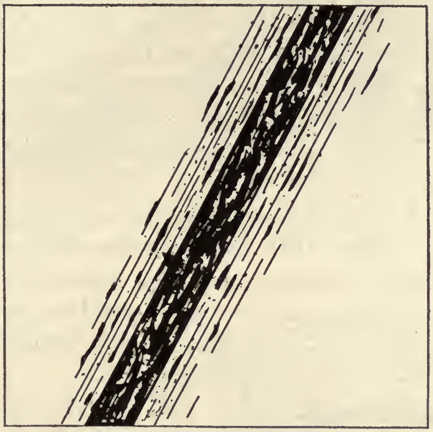

FIG. 88.—Sheeted zone.

Shear Zone.—A shear zone (Fig. 89) is a zone of crushed rock formed by compressive stresses, in which the openings or slips are generally small, tabular, and closely spaced. The individual fissures may be smaller than those of sheeted zones, and in general there is clearer evidence of compression. Ore bodies occupying shear zones are generally deposited in whatever open spaces are available, and the country rock between these spaces may be replaced.

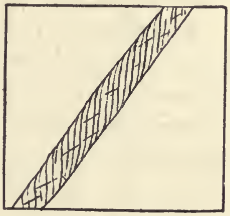

FIG. 89.—Shear zone.

Gash Vein.—Gash veins[1] occupy fissures of moderate extent, usually restricted to one formation and not connected with any very profound earth movement. In southwestern Wisconsin, where they are typically developed, they occupy joint cracks. Usually several small parallel fissures overlap; these are known collectively as a "range." As a rule replacement has occurred along the fissures.[2]

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[1] WHITNEY, J. D.: "Metallic Wealth of the United States," p. 48, 1854.

[2] GRANT, U. S.: Report on the Lead and Zinc Deposits of Wisconsin, with an Atlas and Detailed Map. Wis. Geol. Survey *Bull.* 14, 1906.

BAIN, H. F.: Zinc and Lead Deposits of the Upper Mississippi Valley. U. S. Geol. Survey *Bull.* 294, 1906.

Run.—A ribbon-like, irregular ore body, lying flat or nearly flat, following the stratification, is called a run. Many are formed at the intersections of ore horizons with vertical fissures.[1]

Flats and Pitches.—Flats follow nearly horizontal bedding planes, and pitches follow dipping joint planes (see pages 81, 481). These deposits, which occupy openings formed by the settling of limestone over a shrinking bed, are structurally unique. They have been found only in southwestern Wisconsin.[2]

Lens.—A lens is a rudely tabular body that thins out at the edges. Most tabular bodies, as they have not infinite extent, are strictly lenses, but the term is commonly used to define a relatively small body inclosed in schist and lying parallel to the schistosity (see page 117). Overlapping lenses are shown in Fig. 90. Some of these are older veins deformed during dynamic metamorphism; others are deposited in openings along the schistosity.

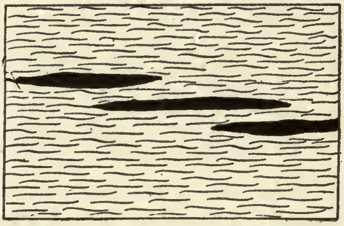

FIG. 90.—Overlapping lenses.

Pod.—A pod is a rudely cylindrical ore body that decreases at the ends like a cigar. The term was formerly used to describe certain bodies long in one and short in two dimensions, inclosed in schist, the long axis lying parallel to the schistosity. It is not much used at present.

Fahlband.—The term "fahlband" was first applied to belts in which disseminated deposits of pyrite, pyrrhotite, and chalcopyrite appear in dark micaceous schists. The original fahlbands at Kongsberg, Norway, are more than 100 feet wide. They are themselves of too low grade to work, but the silver veins near them are enriched. When the sulphides weather and dark minerals such as biotite turn rusty brown, the bands become of lighter color compared with the dark schist between the bands, hence the name (gray bands).

Reopened Veins.—Many veins are fractured and recemented by ore deposited later, thus showing mineralization of two periods. They are called brecciated veins and should be dis-

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[1] JENNEY, W. P.: The Lead and Zinc Deposits of the Mississippi Valley. Am. Inst. Min. Eng. *Trans.*, vol. 22, p. 189, 1894.

[2] CHAMBERLIN, T. C.: The Ore Deposits of Southwestern Wisconsin. *Geology of Wisconsin*, vol. 4, p. 469, 1882.

tinguished from breccia veins, which may be formed by filling spaces around rock fragments. There is much evidence that in

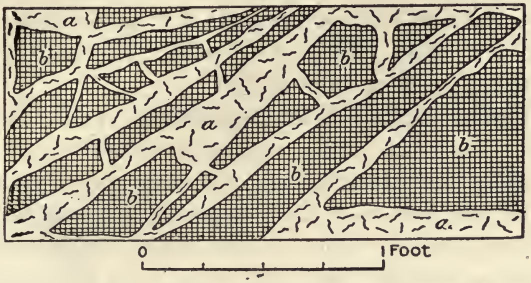

Fig. 91.—Brecciated vein, showing pyrite cut by quartz, Milan mine, New Hampshire. *a*, Quartz; *b*, pyrite.

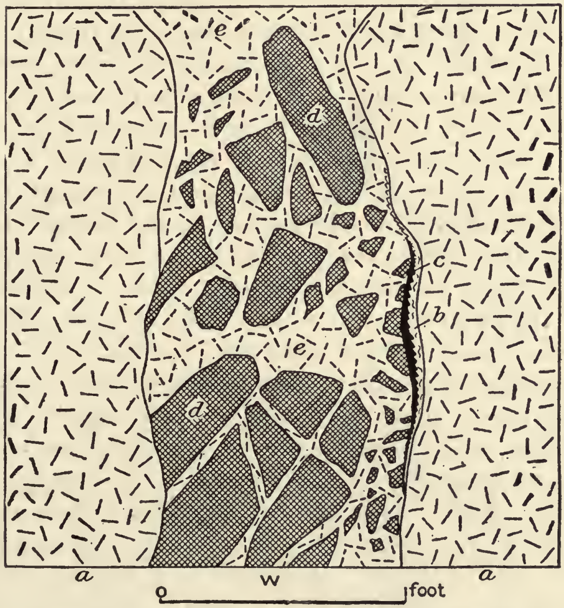

Fig. 92.—Brecciated vein in Mendota mine, near Georgetown, Colorado. Structure due to postmineral movement. *a*, Granite wall rocks of vein; *b*, comb quartz bordering vein; *c*, pyrite; *d*, coarse zinc blende; *e*, uniformly ground-up granite, cemented hard by silica and having a close resemblance to the unbroken granite of the walls. (*After Spurr and Garrey.*)

some places ore deposition and earth movement have gone on during the same period. Thus in a comparatively brief time ores may be formed and then fractured and the fractures in them recemented by ore or gangue. Fig. 91 shows a body of pyrite cut by quartz, the quartz having a rudely reticulated pattern. Fig. 92 shows a fractured vein in granite, which has also been finely fractured and compacted so that it seems now to include fragments of the vein. Some of the northwest veins in the Butte district, Montana, show such features.

Fault Fissures as Seats of Deposition.—Faults are fissures along which there has been movement (see pages 102–112). If the plane of the fault is undulating, long wedge-shaped openings may remain here and there along the fissures (see Fig. 82). Along reverse faults, which in the main are formed deep in the zone of fracture, the larger openings will tend to be closed by the pressure of the overlying load. Faults may remain open longer at moderate depths. For this reason faults which are formed within 1½ miles of the surface and faults which are of the normal type or along which there has been but slight movement are more favorable places for ore deposition than deep-seated faults. Not many large thrust faults contain veins.

Owing to the fact that they bring different rocks into juxtaposition faults with great displacement are in general more easily mapped than fissures along which no displacement is shown. As they are also likely to be longer and deeper, it might appear to follow that they would contain the larger, more persistent ore deposits. This is not generally the case, however, as was pointed out by S. F. Emmons.[1] In a great many districts where large faults are present, the principal ore deposits are in or along fractures that show but little displacement or none. As a result of the movement along the faults the rock may be ground so finely that no supercapillary openings remain. The fissure may be no more permeable to solutions than the country rock on either side. Where many small fractures have been developed on one side of the fault plane, the fractured wall may be more permeable than the fault, which acts as a barrier to solutions rather than as a passageway for them. Many valuable ore deposits, however, are in and along fault fissures.

Because it is nearer the surface and under less pressure when deformation takes place, and because generally it is the block that settles down, the hanging wall is more commonly fractured than the foot wall of a fault. Ore deposits that fill the smaller

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[1] Emmons, S. F.: Structural Relations of Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 16, p. 804, 1888.

synchronous fractures related to the fault plane are more likely to be above the fault than below it, although they may be found in either position.

A list of mining districts containing veins along which no displacement can be measured would include many of the districts of the United States that contain epigenetic deposits. In the Philipsburg district, Montana, there are faults of large displacement known to be older than the veins, but none of the principal veins are along faults of proved displacement. In the Coeur d'Alene district, Idaho, there are several faults that have displacements of many thousand feet, but with the exception of the Bunker Hill and Sullivan lode, none of the larger deposits are along fissures of measured displacement.[1] The ore of this

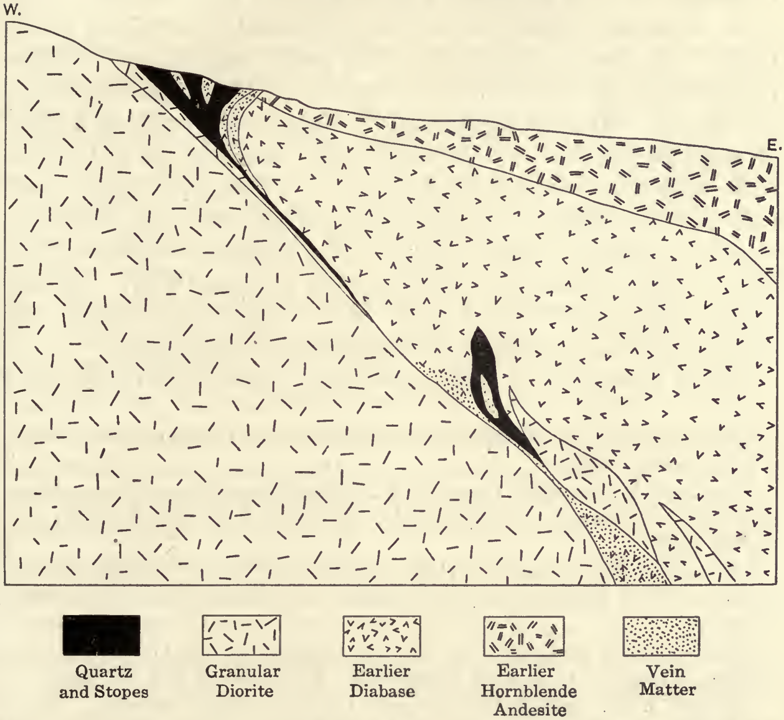

Fig. 93.—Cross-section of Comstock Lode through C and C shaft. (*After Becker, U. S. Geol. Survey.*)

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[1] Ransome, F. L., and Calkins, F. C.: Geology and Ore Deposits of the Coeur de'Alene Mining District, Idaho. U. S. Geol. Survey *Prof. Paper* 62, p. 159, 1908.

lode is generally found in the hanging wall of the principal fault plane.

In many districts, however, there is a close relation of faulting to metallization.[1] The Comstock lode, Nevada (Fig. 93), is developed along and in the hanging wall of a fault of great throw. The Amethyst vein at Creede, Colo.,[2] and some veins of Bullfrog, Nev.,[3] occupy faults of considerable displacement. The Coronado vein at Morenci, Ariz.,[4] follows a fault fissure.

In limestone bodies of ore are commonly developed along faults. At Aspen, Colo.,[5] there are great replacement deposits in limestone at intersections of faults. In the Hornsilver mine, in the San Francisco region, Utah,[6] the ore occurs along a fault of considerable throw. At Globe, Ariz.,[7] some of the ore bodies in limestone are deposited along the Old Dominion fault, especially in the hanging wall, extending irregularly into the limestone. At Bisbee, Ariz.,[8] some of the great ore bodies of the Copper Queen mine are related to the Dividend fault. In the Eureka district, Nevada,[9] most of the largest deposits are in zones of fractured limestone between great fault planes.

In the Nevada City and Grass Valley region, California,[10] the

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[1] Spurr, J. E.: The Relation of Ore Deposition to Faulting. *Econ. Geol.*, vol. 11, p. 601, 1916.

[2] Emmons, W. H., and Larsen, E. S.: A Preliminary Report on the Geology and Ore Deposits of Creede, Colo. U. S. Geol. Survey *Bull.* 530, pp. 42–65, 1913.

[3] Ransome, F. L., Emmons, W. H., and Garrey, G. F.: Geology and Ore Deposits of the Bullfrog District, Nevada. U. S. Geol. Survey *Bull.* 407, 1910.

[4] Lindgren, Waldemar: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 43, pp. 339–346, 1905.

[5] Spurr, J. E.: Geology of the Aspen Mining District, Colorado. U. S. Geol. Survey *Mon.* 31, 1898.

[6] Butler, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent Regions, Utah. U. S. Geol. Survey *Prof. Paper* 80, pp. 166–168, 1913.

[7] Ransome, F. L.: Geology of the Globe Copper District, Arizona. U. S. Geol. Survey *Prof. Paper* 12, p. 140, 1903.

[8] Ransome, F. L.: Geology and Ore Deposits of the Bisbee Quadrangle, Arizona. U. S. Geol. Survey *Prof. Paper* 21, p. 152, 1904.

[9] Curtis, J. S.: Silver-lead Deposits of Eureka, Nev., U. S. Geol. Survey *Mon.* 7, p. 73, 1884.

[10] Lindgren, Waldemar: The Gold-quartz Veins of the Nevada City and Grass Valley District, California. U. S. Geol. Survey *Seventeenth Ann. Rept.*, part 2, p. 259, 1896.

fault throws of the veins are in general small. On the Merryfield and Ural veins, however, great movements have taken place, probably over 1,000 feet along the planes of the faults. In this region nearly all the faults recognized are overthrusts. In the Turquoise district, Arizona,[1] ore-bearing solutions have apparently gained access to shattered limestone along a thrust fault. In the Mother Lode region, California,[2] a large vein system appears to be related to a system of reverse faults.

Subsidiary fractures near either normal or reverse faults are commonly mineralized. Near a normal fault the fractures in its hanging wall are the more likely to be mineralized, as is illustrated in many of the districts above noted. In the Amethyst lode, Creede, Colo., where the fault itself is heavily mineralized, ore is found also in subsidiary fractures in both walls, but a larger number of fractures are in the hanging wall. At Butte, Mont., the older, easterly (Anaconda) system of fissures were formed with little or no movement parallel to the fissures. The veins that fill these fissures are regular, nearly uniform, and very persistent, some of them having been stoped for thousands of feet along their strike, and they show little if any tendency to develop ore shoots. These veins are crossed by fissures of later age,[3] which have displaced them. The later faults are usually from 5 to 20 feet wide and exhibit one or more planes of movement marked by tough clay a quarter of an inch to 5 or 6 inches thick. Some of these faults are of the reverse type. They have been explored along the strike for more than a mile and at intervals contain valuable ore shoots. The ore shoots are very irregular in form and range from mere pockets to masses 1,000 feet long and 2,000 feet deep or more. Their width ranges from a knife-edge to 20 feet, or the entire width of the fault zone. Complete replacement of the crushed country rock by ore minerals has locally obliterated the evidence that the original fissure was due to faulting. The barren places in the faults are dry, but the ore is wet, and Sales maintains that the metal-bearing waters traversed only the places now mineralized and that the crushed granite and attrition clay have formed impermeable barriers

[1] Ransome, F. L.: The Turquoise Copper-mining District, Arizona. U. S. Geol. Survey *Bull.* 530, p. 133, 1913.

[2] Ransome, F. L.: U. S. Geol. Survey *Geol. Atlas,* Mother Lode District Folio (No. 63), 1900.

[3] Sales, R. H.: The Localization of Values in Ore Bodies and the Occurrence of Shoots in Metalliferous Deposits. *Econ. Geol.,* vol. 3, p. 326, 1908.

that effectively sealed off certain parts of the faults. There are many other known examples of faults, older than veins, that have influenced the courses of solutions by damming them off.[1]

Influences of Rock Structure on Fissuring.—In some districts fissures show a strong tendency to follow bedding planes, planes of schistosity, contact planes, dikes, and other structural features. This tendency is more noticeable where such planes are regular and strongly developed. They are generally planes of weakness and therefore favor rupture. They do not localize a rupture completely, however, except where they are favorably oriented with respect to the forces that are applied. Generally the fissures follow such planes at some places and cut across them at others. They may follow a regular contact along both strike and dip, or only along the strike. Many bedding-plane deposits are simply veins which follow bedding-plane fissures. A sheeted zone, consisting of closely spaced parallel fissures, may be formed where highly schistose and somewhat brittle rocks are fractured by compressive stresses. Many igneous dikes localize fracturing and ore deposition because they are more brittle than associated rocks. Planes of contact between two rock formations in many districts are likewise planes of rupture. On the Mother Lode, in California,[2] many of the veins follow the planes of schistosity or contacts between two formations. At Cripple Creek, Colo.,[3] many of the veins follow dikes or contacts between the dikes and other rocks. Similar relations are shown near Georgetown[4] (Fig. 94), and at Creede, Colo.; at Bullfrog, Nev.;[5] at Morenci, Ariz.[6] (Coronado vein), and elsewhere.

Many fissure veins formed near the surface and inclosed in

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[1] RANSOME, F. L.: The Relation of Certain Ore-bearing Veins and Gouge-filled Fissures. *Econ. Geol.*, vol. 3, pp. 331–337, 1909.

[2] RANSOME, F. L.: U. S. Geol. Survey *Geol. Atlas,* Mother Lode District Folio (No. 63), 1900.

[3] LINDGREN, WALDEMAR, and RANSOME, F. L.: Geology and Gold Deposits of the Cripple Creek District, Colorado. U. S. Geol. Survey *Prof. Paper* 54, p. 154, 1906.

[4] SPURR, J. E., and GARREY, G. H.: Economic Geology of the Georgetown Quadrangle, Colorado, with General Geology by S. H. Ball. U. S. Geol. Survey *Prof. Paper* 63, 1908.

[5] RANSOME, F. L., EMMONS, W. H., and GARREY, G. H.: Geology and Ore Deposits of the Bullfrog District, Nevada. U. S. Geol. Survey *Bull.* 407, 1910.

[6] LINDGREN, WALDEMAR: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 43, p. 341, 1905.

schists do not follow the schistosity. In the middle and upper part of the zones of fracture the rocks are under less load and the separate blocks may move more freely than at greater depths. Thus, at Silver Plume and in some districts in the San Juan region Colorado, the lodes cut across the schistosity at large angles. Not all deposits that follow the bedding planes of schists are fissure veins. Some of them are dynamically metamorphosed deposits of various types. These are discussed on page 114.

Bedding-plane Deposits.—Epigenetic deposits may be restricted to certain beds because those beds are permeable, because they are chemically more hospitable, or because they have been shattered or fissured by movement. In the Black Hills of South Dakota,[1] numerous small fissures or "verticals" traverse beds of quartzite and limestone. In the quartzite there is little or no deposition, but the limestone above is extensively replaced. The solutions, which were not competent to replace the quartzite, when they reached the

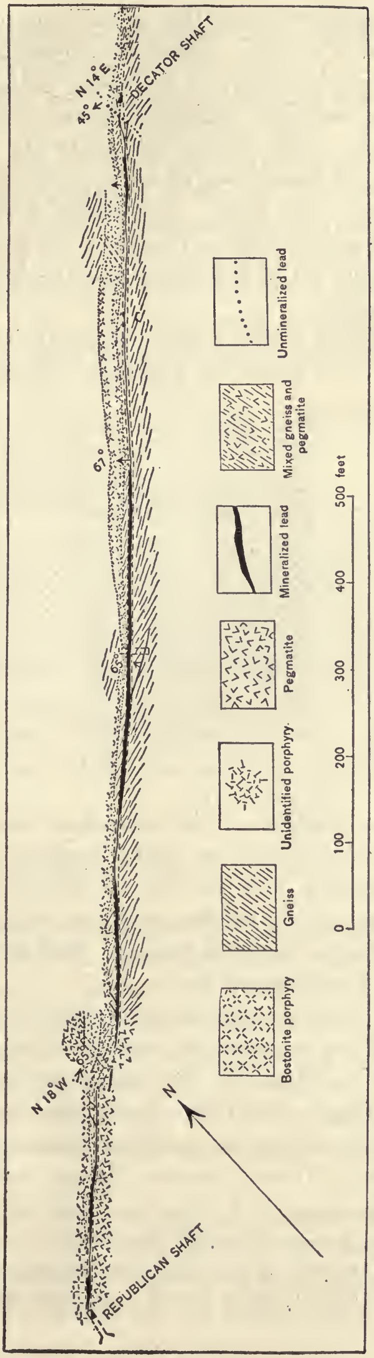

FIG. 94.—Vein formed in fracture on border of dike. Adit level, Little Mattie Mine, Idaho Springs, Colorado. (*After Spurr and Garrey.*)

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[1] IRVING, J. D.: Economic Resources of the Northern Black Hills. U. S. Geol. Survey *Prof. Paper* 26, pl. 19, 1904.

limestone spread through a large mass and deposited flat, tabular bodies of ore. Extensive deposits at Rico, Colo.,[1] were formed by replacement in limestone below shale. The vertical fissures that cross the limestone divide into many small fractures in the shale. Just below the shale the limestone is replaced by long, flat ribbons of ore which cap the verticals and follow the stratification of the rock. The shape of a section of the deposit may be compared with a T-square, if the upper bar of the square is exaggerated in thickness and the lower bar greatly exaggerated in length.

Some bedding-plane deposits in limestone are not related to beds of shale or quartzite above or below. They follow the stratification of the limestone because certain beds were more permeable to the metal-bearing solutions. This greater permeability may be due to differences in composition or in pore space in the original rock, or to subsequent fissuring or faulting along the bedding planes. Bedding-plane deposits are illustrated by Figs. 95 and 96.

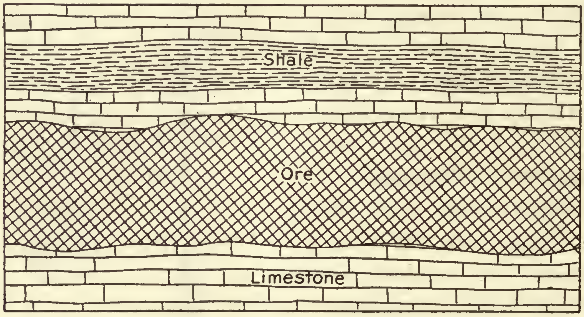

Fig. 95.—Cross-section of bedding-plane deposit in limestone.

Unless there is a crosscutting dike, an older vein, or some other plane of reference, it may be difficult to discover movement along the bedding, for the processes of replacement may obliterate evidences of movement, such as friction breccia or gouge. Small movements along bedding planes are doubtless very common in areas of tilted strata. Many bedding-plane deposits of fairly

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[1] Rickard, T. A.: The Enterprise Mine, Rico, Colorado. Am. Inst. Min. Eng. *Trans.*, vol. 26, p. 906, 1896.

Ransome, F. L.: The Ore Deposits of the Rico Mountains, Colorado. U. S. Geol. Survey, *Second Ann. Rept.*, part 2, p. 291, 1901.

uniform width are inclosed in limestone that appears to be homogeneous above, below, and in the plane of the deposit.

Some of the criteria by which bedding-plane deposits are distinguished from sedimentary ores are difficult to apply. The origin of the ores in beds is one of the most perplexing problems of geology. Concerning the genesis of the ore deposits of the most productive copper district in Germany (Mansfeld), and of the most productive gold district in the world (Witwatersrand, South Africa), even after extensive studies by able investigators, opinions differ widely. The deposits of each of these districts are regarded by many as sedimentary bedded ores and by many others as epigenetic bedding-plane deposits.

Long, Slender Deposits and Equidimensional Deposits.—Where two thin tabular openings intersect, a long, slender opening wider than either or a line of more intense fracturing may be formed at the intersection. If such openings become seats of mineralization the deposits may be chimneys or ribbons of ore, their form depending upon the nature and attitude of the rocks involved. Intersections of dikes or of bedding planes with fissures similarly yield long, thin lines of fracturing that are favorable places for deposition (see Figs. 97, 98). Fracturing is likely to be more extensive where the planes intersect at small angles.

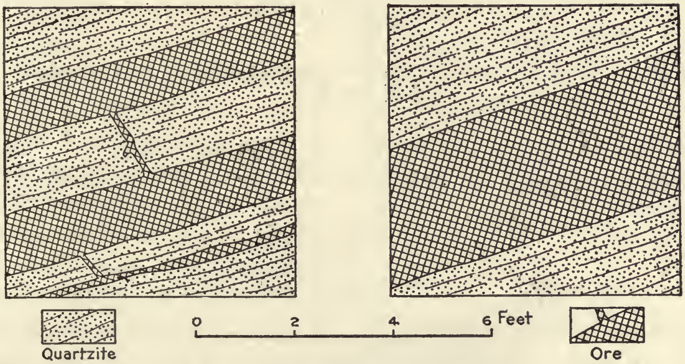

Fig. 96.—Cross-sections of bedding-plane deposits in quartzite.

Where several fissures intersect and are suitably spaced, openings or shattered masses that are nearly equidimensional may be formed. Some ore bodies assumed to be related to such openings or shattered zones are nearly isodiametric, or rudely spherical.

Many chimneys, ribbons, and isodiametric masses of ore are replacement deposits, and it may be difficult to determine whether or not such deposits are related to large open spaces at intersections. In many districts the localization of the ore at such places is due to more extensive fracturing of the wall rocks near the intersections rather than to the widening of open spaces.

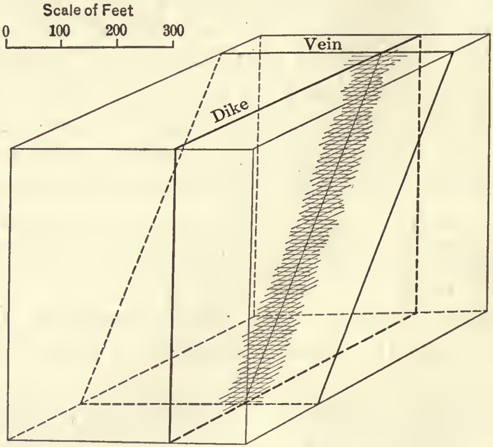

Fig. 97.—Stereogram showing an ore shoot formed at intersection of dike and vein.

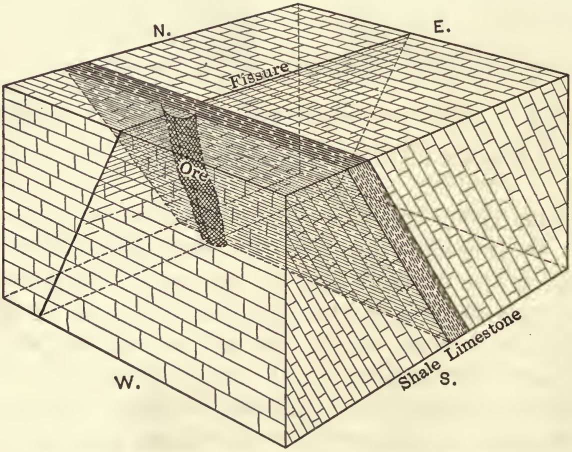

Fig. 98.—Stereogram showing an ore shoot formed at intersection of fissure with limestone below a shale bed. The ore makes out from the fissure along the bottom of the shale bed. (*After Butler, U. S. Geol. Survey.*)

Chimneys of ore in limestone are not uncommon. Some slender ore bodies in limestone are curved into sigmoidal or snake-like forms; some are very irregular: miners call them "corkscrews." As a rule such deposits are formed at the intersections of fissures or joint planes, or both. The circulation may follow a fissure here, a bedding plane there, or a joint plane at another place. Obviously "blocking out" ore in such deposits requires numerous and closely spaced exposures. A continuous ore body may be formed by replacement of the rock locally along any set of planes or along intersections, and it is generally unsafe to predict the position of such an ore body beyond the point of exploration. The ore body may end abruptly at any place; a chimney followed upward may thus become what the miner terms a "blind chimney," or one that does not extend to the surface.

A mass of ore that is nearly equal in all dimensions is often termed a "chamber" or a "chambered deposit." Many chambered deposits are formed by the replacement of limestone. Some of them are below shales or sheets of porphyry or other igneous rocks; but others are in limestone and show no obvious relation to any well-defined structural feature. Presumably they are localized at intersections of fractures or where there has been a maximum amount of fracturing. Many of them are puzzling, for the veinlets, filled fractures, or replaced bedding-plane fissures which lead to some of them are small compared with the chamber of ore. When the ore is removed and the walls are closely scrutinized the openings through which solutions may have entered are more readily found. Veins that locally are greatly enlarged have been termed "chambered veins"[1] (see Fig. 99).

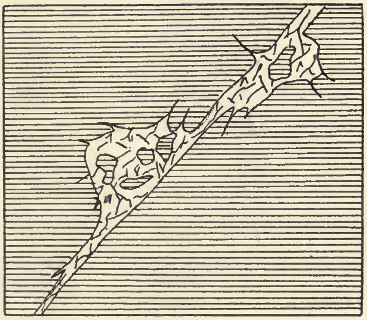

FIG. 99.—Chambered vein. (*After Becker, U. S. Geol. Survey.*)

Anticlinal Deposits; Saddle Reefs.—In many districts of folded rocks ore deposits are concentrated on the axes of folds, especially at the crests of anticlines (Figs. 100 to 103). This

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[1] BECKER, G. F.: Geology of the Quicksilver Deposits of the Pacific Slope. U. S. Geol. Survey *Mon.* 13, p. 411, 1881.

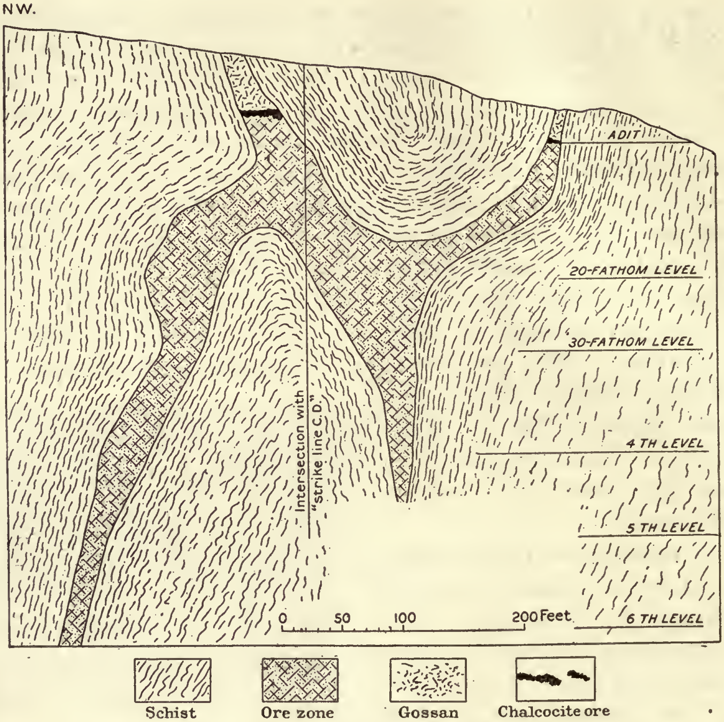

Fig. 100.—Vertical section of Mary Mine, Ducktown, Tenn.

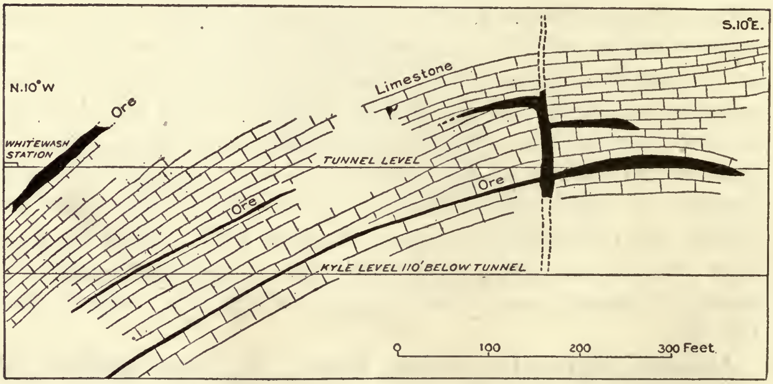

Fig. 101.—Vertical section of Hope Mine, near Philipsburg, Mont., showing thickening of deposit at crest of anticline.

relation to the structure is shown not only in schistose rocks that have been closely folded, but also in rocks that are not schistose and that have been thrown into moderately open folds. Five possible modes of origin for such deposits should be considered.

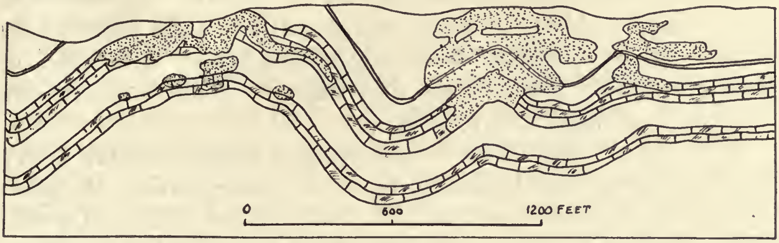

Fig. 102.—Deposits formed on and near anticlines, Tombstone, Arizona. (*After Church.*)

1. The folding of ore bodies after their deposition may be attended by thickening at the crests of folds and thinning along their limbs.

2. Thin beds of limestone or other rocks compressed into folds and thickened at crests of anticlines may have been replaced by mineral-bearing solutions (see Fig. 100).

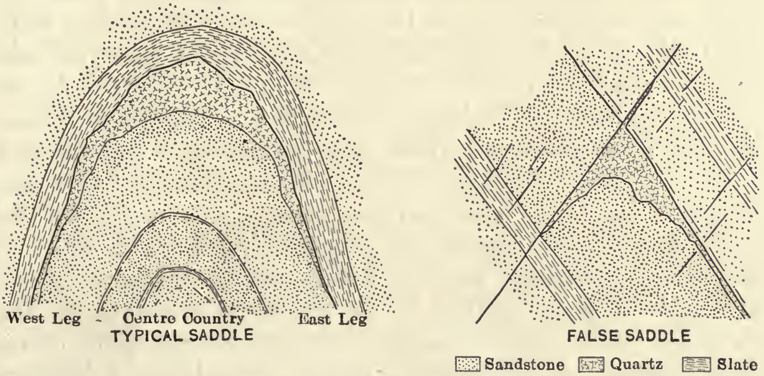

Fig. 103.—Sketch showing typical saddle and "false saddle." (*After Richard.*)

3. Mineral matter may be introduced into openings at axes of folds where brittle beds have been fractured, or where beds have been separated by movement (see Figs. 79, 80).

4. Segregation of mineral matter in folds may be accomplished by solutions during dynamic or regional metamorphism.

5. In igneous and in sedimentary rocks fissures that have approximately parallel strikes and that cross and dip in opposite

directions may be more heavily mineralized at and near the lines of their intersections (see in Fig. 103).

1. If rocks are folded after ores have formed in them, the ore bodies are likewise folded. Certain textures result, depending upon the intensity of the folding and the mineral composition of the deposits. Many iron-ore deposits in the Lake Superior region have been folded after they were formed. Examples of folded sulphide deposits are also known. These deposits are discussed on pages 113 to 123.

2. When a series of rocks consisting of sandy or other heavy beds inclosing thin limestone layers is closely folded, the limestone may be greatly distorted. Under heavy pressure the soft lime carbonate is somewhat mobile and is squeezed into places where pressures are lowest. Thus a limestone bed is likely to become thick on the crests of anticlines and thin on the limbs, where it may even be squeezed out entirely. If subsequently all the limestone is replaced by ore, the ore body will be largest where the limestone bed was thickest. The copper sulphide ores of Ducktown, Tenn., which replace deformed limestone lenses, are greatly concentrated on the crests of anticlines (Fig. 100).

3. Where brittle rocks alternating with less brittle ones are flexed, fracturing is likely to be localized near the crests of anticlinal folds or near troughs of synclinal folds. Larger fractures are more readily formed at the crest of an anticline than at the trough of a syncline, because a bed there is nearer the surface and under less pressure Under some conditions, which can not now be accurately defined but which doubtless prevail under moderate load, beds glide one over another and spaces parallel to the beds are formed at the crests of folds. This mode of formation of openings may be illustrated by flexing the sheets of a tablet of glazed paper. If the glued end is held firmly and the other end is pushed toward it without exerting much downward pressure on the leaves, a number of saddle-like openings are formed, one above another (Fig. 80).

Many bedding-plane deposits in limestone are thicker at the crests of folds. Ore folds, anticlinal deposits, saddles, and troughs may be developed also in sandstones and shales, or in slates, as they are at Bendigo, Australia,[1] where the saddle reef was first recognized.

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[1] Dunne, E. J.: Victoria Min. Dept. *Quart. Rept.*, 1888.

Rickard, T. A.: The Bendigo Gold Field. Am. Inst. Min. Eng. *Trans.*, vol. 20, pp. 463–545, 1890.

4. Some sulphide ores that follow the cleavage planes of schists are assumed to have been deposited by segregation during dynamic or regional metamorphism, but probably the segregation of metals under these conditions is not extensive (see page 118).

5. The localization of ore bodies at the intersections of fissures is discussed on page 199.

There are many examples of anticlinal deposits. The famous saddle reefs of Bendigo, Victoria, are mentioned above. In this region the prevailing rocks are sandstones and slate. There are three principal productive anticlines which may be followed 5 to 14 miles along their strike. On the axes of these anticlines the saddles of auriferous quartz are spaced one above another at intervals in depth of 300 feet or more. Some of the ore bodies have been stoped for thousands of feet along their strike, and workings have extended below 4,300 feet. The anticlinal axes are not horizontal but dip eastward; the ore bodies along their crests plunge at angles as great as 20°. The saddles are connected by quartz-filled veins and by basic dikes that are later than the ore. There are also "inverted saddles" or troughs of ore, but these are less valuable. About 22 miles south of Bendigo, in the Castlemaine field,[1] Silurian rocks are intruded by granodiorite. Gold-bearing saddle reefs are developed in the closely folded sediments. Veins are present also in fissures and faults.

At Hargraves, New South Wales,[2] slates and tuffs are intruded by granitic rocks. The sediments are closely folded, and saddle reefs of siliceous gold ore are developed in them along the axial planes of anticlines. Flat-lying quartz veins connect the several anticlines.

The Rammelsberg mine,[3] in Germany, is mentioned on page 122.

The deposits of Mysore, India, among the greatest gold deposits of the world, are characterized by numerous puckerings or folds. The country is an area of conglomeratic hornblende schists and quartzite, with which are associated granite and aplite. The principal lode is the Champion reef, which is developed for 4 miles along the strike and 3,740 feet on the incline in depth. The average width is about 4 feet and the dip about 55°. The

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[1] BARAGWANATH, W.: The Castlemaine Gold Field. Victoria Geol. Survey *Mem.* 2, 1903.

[2] PITTMAN, E. F.: Mineral Resources of New South Wales, pp. 33–36, New South Wales Geol. Survey, 1901.

[3] LINDGREN, WALDEMAR, and IRVING, J. D.: The Origin of the Rammelsberg Ore Deposit. *Econ. Geol.*, vol. 6, pp. 303–313, 1911.

minerals are quartz, tourmaline, pyrite, arsenopyrite, pyrrhotite, chalcopyrite, zinc blende, and galena.[1]

Anticlinal reefs are developed in slates and quartzites in the gold fields of Nova Scotia.[2] The folded metamorphosed sediments are cut by granite. The minerals present are quartz, pyrite, chalcopyrite, galena, sphalerite, and arsenopyrite.

The argentiferous lead and zinc deposits of Broken Hill, New South Wales,[3] are also of the saddle-reef type. In this district, which is one of the most productive in the world, the ore bodies conform to the planes of schistosity. They carry abundant garnet in the gangue, and it is possible that they were formed by the replacement of calcareous beds. At Ducktown, Tenn.,[4] anticlinal deposits of garnetiferous sulphides replace bodies of deformed limestone.

In several districts of the United States where rocks are folded less closely than in the areas above mentioned anticlinal ore bodies are formed by replacement in limestone. They appear to have been deposited at moderate depths by solutions at moderate temperatures, in zones of maximum fracturing. At Hope Hill, near Philipsburg, Mont.,[5] the bedding-plane deposits in limestone are greatly expanded near the crests of anticlines, where fracturing was probably greatest (see Fig. 100). At Elkhorn, Mont.,[6] sulphide ores are develoepd in limestone below a bed of shale. The ore bodies are localized along an anticlinal axis that plunges rather steeply and bifurcates in depth.

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[1] Smeeth, W. F.: Mysore, Dept. Mines, *Rept.* 1899.

[2] Faribault, E. R.: The Gold Measures of Nova Scotia and Deep Mining. Canadian Min. Inst. *Jour.*, vol. 2, pp. 119–162, 1899.

Rickard, T. A.: The Domes of Nova Scotia. Inst. Min. and Met. *Trans.*, vol. 21, pp. 506–560, 1912.

[3] Pittman, E. F.: New South Wales, Geol. Survey *Rec.*, vol. 3, pp. 45–49, 1892.

Jaquet, J. B.: "Geology of the Broken Hill Lodes," Sydney, 1894.

Clark, Donald: "Australian Mining and Metallurgy," p. 267, 1904.

Moore, E. S.: Observations on the Geology of the Broken Hill Lode, New South Wales. *Econ. Geol.*, vol. 11, pp. 327–348, 1916.

[4] Emmons, W. H., and Laney, F. B.: Preliminary Report on the Mineral Deposits of Ducktown, Tenn. U. S. Geol. Survey *Bull.* 470, p. 151, 1911.

[5] Emmons, W. H., and Calkins, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, p. 214, 1913.

[6] Weed, W. H.: Geology and Ore Deposits of the Elkhorn Mining District, Jefferson County, Montana. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 2, p. 472, 1901.

At Tombstone, Ariz.,[1] argentiferous deposits replacing limestone are on or near the axes of anticlines. In the Kelly district, near Magdalena, N. Mex.,[2] the ore is developed in limestone as three long parallel shoots, pitching with the beds and coinciding with the axes of gentle folds. At the Robinson mine, near Concord, Maine,[3] a small lead-zinc deposit in limestone occupies the axis of an anticline. The ore body of the Clover Leaf gold mine, in the Black Hills, South Dakota,[4] which is developed on a plunging anticlinal fold in schist and slates, is greatly thickened on the crest of the fold.

Synclinal Deposits; Inverted Saddles; Troughs.—In some mining districts the ores are concentrated in synclines or structural troughs. Synclinal deposits may be formed by several groups of processes corresponding to those mentioned above in the discussion of the origin of anticlinal deposits. They may be formed by the replacement of limestone beds at synclines, by the filling of openings between two beds at synclines, or by replacement in zones of fracturing on synclines. During dynamic metamorphism tabular deposits may be folded to form synclines. In areas of closely folded rocks openings due to fracturing are probably less commonly developed along synclinal axes or planes than along anticlinal planes because in a folded series of beds any given zone that is favorable for the deposition of ore will lie at lower altitudes in synclines than in anticlines, and in a syncline the favorable zone is likely to be covered by a greater and therefore heavier mass of overlying beds. Ores formed along anticlines or along synclines are characteristically developed in the deep vein zone or at moderate depths. Ore folds are comparatively rare in deposits formed by ascending thermal waters at shallow depths. "False saddles" or "false inverted saddles," both of which are formed near lines of junction and along intersecting fractures, may be formed at all depths. Although anticlinal deposits or saddle reefs are more numerous and generally

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[1] Blake, W. P.: Geology and Veins of Tombstone, Ariz. Am. Inst. Min. Eng. *Trans.*, vol. 10, p. 334, 1882.

Blake, W. P.: Tombstone and Its Mines. *Idem*, vol. 34, p. 668, 1904.

[2] Lindgren, Waldemar, Graton, L. C., and Gordon, C. H.: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68, p. 251, 1910.

[3] Emmons, W. H.: Some Ore Deposits in Maine and the Milan Mine, New Hampshire. U. S. Geol. Survey *Bull.* 432, p. 48, 1910.

[4] Irving, J. D.: Economic Resources of the Northern Black Hills. U. S. Geol. Survey *Prof. Paper* 26, p. 212, 1904.

more clearly defined than synclinal deposits or inverted saddles, examples of the latter are not rare. Some are found in the famous Bendigo district of Victoria, Australia,[1] where anticlinal deposits are conspicuously developed. The famous zinc deposits of Franklin Furnace, N. J., form pitching troughs (see page 487). At Franklin, British Columbia,[2] the deposits, which were formed later than the regional metamorphism of the associated sedimentary rocks, are on compressed synclines where the mashed and sheared rocks have afforded channels for solutions. Some of the deposits of Bisbee, Ariz., lie in a gentle syncline. This fold, however, appears to be only one of several features that have influenced the localization of the ore deposits (see page 367). Other examples of deposits formed in open synclines are known.[3]

Many ore deposits and protores enriched by superficial alteration occur in pitching troughs or synclines, especially where a body of fractured permeable protore lies in a trough that is formed by impermeable rocks. Such troughs are likely to be paths of descending solutions that may enrich the ore by dissolving and removing valueless constituents or that may deposit valuable ores (see page 301).

FRACTURE SYSTEMS IN MINING DISTRICTS

Although the fractures and veins in many mining districts show great differences in their distribution, there are certain fracture patterns which are well-recognized recurring types. In some districts the fractures of one system or one set are approximately parallel in strike and dip, and those of a second system are approximately parallel to the first in strike but dip in an opposite direction. Such groups have been termed "conjugated" fractures. A coördinate set of fractures consists of a group of parallel or nearly parallel fractures that is crossed by a second group of nearly parallel fractures striking in a different direction. The fractures of two conjugated systems or of a conjugated set may be cut by those of two other conjugated systems striking approximately at right angles to them. If the fissures of the latter

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[1] RICKARD, T. A.: The Bendigo Gold Field. Am. Inst. Min. Eng. *Trans.*, vol. 20, pp. 463–545, 1892.

[2] DRYSDALE, C. W.: Geology of the Franklin Mining Camp, British Columbia. Canada Geol. Survey *Mem.* 56, p. 166, 1915.

[3] LAWSON, A. C.: Ore Deposition in and near Intrusive Rocks by Meteoric Waters. Cal. Univ. Dept. Geol. *Bull.*, vol. 8, pp. 219–242, 1914.

likewise dip in opposite directions, there will then be altogether four systems of fracture, or two coördinated conjugated sets. Such systems are commonly attributed to compressive stresses.

Conjugated Systems.—Examples of conjugated or coördinated systems developed in various degrees of perfection are found in many districts. Among the best-known examples are those of the Nevada City and Grass Valley region, California,[1] where there is a northerly system of veins that dip about 35° to 40° east or west (see Fig. 104), and an easterly system that dip either north or south at high or low angles. In the Ophir district, California,[2] vein systems on the strike make angles of intersection of about 45° (see Fig. 105). Other examples are in the Telluride region,[3] San Juan Mountains, Colorado, and the Needle Mountains,[4] also in Colorado. Foreign examples include the tin veins of Cornwall, England, the silver veins of Freiberg, Saxony, the silver-cobalt veins of Schneeberg, Saxony, and a great many others.

The coördinated and conjugated sets of fractures are generally supposed to have been formed about the same time and by the relief of the same stresses. If the intersections of veins of the two systems

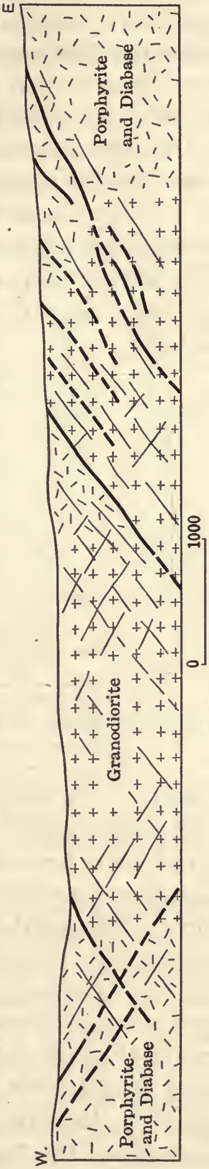

FIG. 104.—Cross-section of conjugated vein system near Grass Valley, Calif. (*After Lindgren, U. S. Geol. Survey.*)

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[1] LINDGREN, WALDEMAR: The Gold-quartz Veins of Nevada City and Grass Valley Districts, California. U. S. Geol. Survey *Seventeenth Ann. Rept.*, part 2, p. 13, 1896.

[2] LINDGREN, WALDEMAR: The Gold-silver Veins of Ophir, Calif. U. S. Geol. Survey *Fourteenth Ann. Rept.*, part 2, p. 253, 1893.

[3] PURINGTON, C. W.: Preliminary Report on the Mining Industries of the Telluride Quadrangle, Colorado. U. S. Geol. Survey *Eighteenth Ann. Rept.*, part 3, p. 745, 1897.

[4] IRVING, J. D.: U. S. Geol. Survey *Geol. Atlas*, Needle Mountains Folio (No. 131), 1906.

should show that those of one system are everywhere cut by those of the other set, it would be inferred that the two sets of fissures were formed at different times.

Horse-tail Structure.—In many vein systems there is a major fracture from which numerous minor fractures extend. The minor fractures commonly make angles of 30° to 60° with the major fracture and are rudely parallel one to another. Where they are closely spaced large ore bodies may be formed along them. If the country rock between them is highly shattered wide zones of mineralization may be developed. At Butte, Mont.,[1] on the deeper levels of the Leonard mine, the axes of the principal deposits strike at a large angle with the main limiting fracture. In some deposits in the Butte district zones of mineralization nearly 200 feet wide have been formed in the fractured rock between two outlining master fractures. The cross fractures are themselves connected by many still smaller fractures. The multiplicity of fractures gave the solutions free access to great bodies of rock, and mammoth ore deposits were formed by replacement of the shattered zones. In some of these deposits it can be shown that the minor fractures were formed at the same time as the outlining major fractures. The minor fractures do not cross but join the major fractures, and all carry similar ore. In some examples the area of cross fracturing is

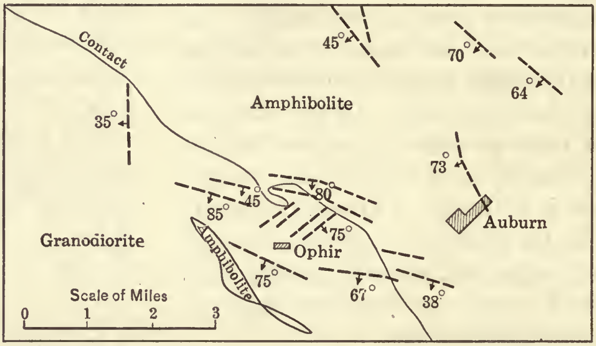

Fig. 105.—Map of the principal vein systems near Ophir and Auburn, Calif. (*Based on map by Lindgren, U. S. Geol. Survey.*)

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[1] Sales, Reno: Ore Deposits of Butte, Montana. Am. Inst. Min. Eng. *Trans.*, vol. 46, pp. 13, 17 (see particularly Fig. 2), 1913.

Weed, W. H.: Geology and Ore Deposits of the Butte District, Montana. U. S. Geol. Survey *Prof. Paper* 74, pp. 203–213, 1912.

sharply limited in only one direction by master fractures, as shown in the Leonard mine (Fig. 106). Toward the southeast the cross fractures join and become less closely spaced, the highly fractured zone gradually giving way to less fractured rock. It is believed that the fracturing is due to compressive stresses acting on a mass that was free to move in one direction. If a block of wood is compressed in a testing machine with one end of the block free to move laterally, structure closely resembling the horse-tail structure may be developed.

Parallel Systems.—In many mining districts all or nearly all the ore veins are approximately parallel. Many parallel systems have commonly been regarded as resulting from compressive stresses, although the analogy with the results of experiments in deformation is obviously not so close as that with coördinate systems. Variations in stresses, heterogeneity of materials, etc., may favor the development of only one system. In some districts there may be two systems of fractures of which only one is mineralized or filled with vein materials. The other system, where represented by joint planes only, is inconspicuous. There are many more mining districts in which the ore veins may be referred to a single parallel system than to two coördinated or conjugated sets. Examples of systems of rudely parallel veins

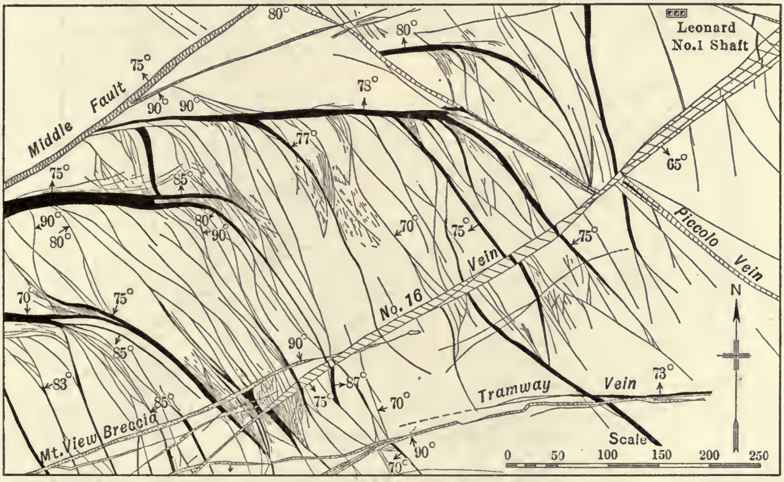

FIG. 106.—Plan of a portion of the Leonard Mine, Butte, Montana, showing transverse fissuring in Colusa-Leonard vein. (*After Sales.*)

include the earlier copper lodes of Butte, Mont.; the silver-gold lodes of Philipsburg, Mont.; some of the districts of California and Idaho (see Fig. 107); several districts in Colorado; and many others. This is probably the most common type of vein system.

Radial Patterns.—Systems of radial igneous dikes are shown in many districts, but radial patterns of ore veins are not common. They are represented in some degree of perfection at Cripple Creek, Colo.,[1] where the principal fissures are confined to an area but little larger than the volcanic neck in and around which the lodes are grouped (Fig. 108). Basic dikes are arranged radially about the volcanic center, and many of the veins follow the dikes. The "hubs" of the Atlin district, British Columbia, described by Cairnes,[2] are radial patterns less perfectly developed.

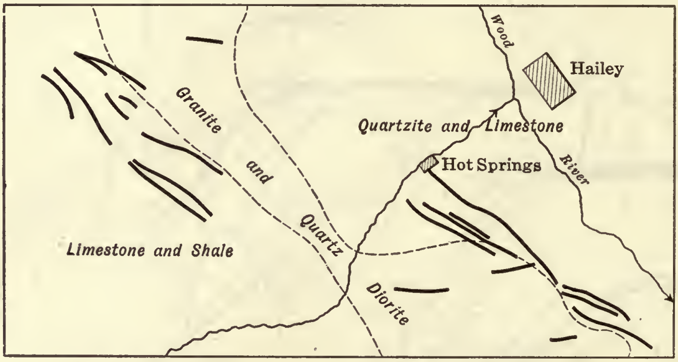

FIG. 107.—Map of vein systems in Wood River district, Idaho. (*Based on map by Lindgren, U. S. Geol. Survey.*)

Irregular Patterns.—Irregular patterns of ore veins are not uncommon. In these the veins occupy fissures that can not be referred to systems. Such complex fracture patterns, as pointed out by Chamberlin,[3] may be regarded as shallow-seated phenomena related to the more simple movements which take place at greater depths. As would be supposed, the patterns of this

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[1] LINDGREN, WALDEMAR, and RANSOME, F. L.: Geology and Gold Deposits of the Cripple Creek District, Colorado. U. S. Geol. Survey *Prof. Paper* 54, p. 167, 1906.

[2] CAIRNES, D. D.: Portions of Atlin District, British Columbia. Canada Geol. Survey *Mem.* 37, p. 84, 1913.

[3] CHAMBERLIN, T. C.: The Fault Problem. *Econ. Geol.*, vol. 2, p. 590, 1907.

character are developed more commonly in areas of comparatively late deposition where the deposits were formed near the surface. The ledges at Goldfield, Nev.,[1] form an irregular pattern (Fig. 109), although certain small portions of this area show

FIG. 108.—Plan of the principal fissures of the Cripple Creek district, Colorado on plane 9,500 feet above the sea. (*Based on map by Lindgren and Ransome, U. S. Geol. Survey.*)

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[1] RANSOME, F. L.: Geology and Ore Deposits of Goldfield, Nevada. U. S. Geol. Survey *Prof. Paper* 66, p. 151, 1909.

tendencies to parallelism. The lodes of Cobalt, Ontario,[1] are likewise unsystematized.

Fig. 109.—Plan showing irregular distribution of fractures in Goldfield district, Nevada. (*After Ransome, U. S. Geol. Survey.*)

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[1] Miller, W. G.: The Cobalt-nickel Arsenides and Silver Deposits of Temiskaming, Ontario. Ontario Bur. Mines *Rept.*, vol. 19, part 2, p. 6, 1913.

Topographic Expression of Deposits.—The topographic expression of a deposit depends upon the relation between the rates at which the deposit and the country rock are eroded. If the deposit is more resistant to erosion than the country rock, the latter will be removed more rapidly and the lode may crop out as a ridge or knob. If the country rock is the more resistant the deposit may occur at the bottom of a slight depression where blocks of hard vein quartz are mingled with the rock débris. If there is no marked difference between the rates of erosion of the deposit and the country rock, the deposit may be found in any topographic position, and for the lode deposits of the western part of the United States this is the most common condition. There is in few places a conspicuous relation between the outcrops of the deposits and the large features of the topography, although in many camps some of the minor features of the relief are controlled by the lodes.

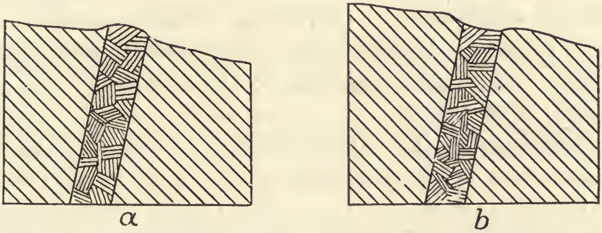

Fig. 110.—*a*, Outcrop of lode more resistant than country rock; *b*, outcrop of lode less resistant than country rock.

It is not unusual to find differences in topographic expression among the deposits of a single district, or even in a single lode. At one place it may crop out as a ridge; at another, along a ravine. The difference in resistance must be great before permanent relief is established, for the rock of a ridge is in an exposed position and is therefore the more readily attacked by agents of weathering. In a region that has not been recently glaciated a resistant ore may crop out as a small ridge. Siliceous ores in limestones and in other soluble rocks generally stand conspicuously above the surrounding country. Magnetite resists erosion longer than pyrite, and its deposits may crop out as ridges. In the igneous rocks of many regions siliceous deposits form conspicuous ridges, but if the siliceous deposits are much fractured they mark shallow ravines and saddles where they cross ridges (see Fig. 110).

In quartzite siliceous deposits do not form conspicuous topographic features. Pyrite and other sulphides alter more readily than quartz, and few highly pyritic ores show marked topographic relief. In resistant rocks pyritic ore bodies, especially ore bodies that are fractured, may form depressions.

The great majority of ore bodies are rudely tabular; accordingly the intersection of such a body with the surface is in general expressed as a band, which is usually curved, the curvature depending on the topography and the dip of the lode, or on an actual bend of the lode along the strike.

In a few districts lodes are traced almost continuously for hundreds of yards by the topographic expression of the outcrops or by vein matter exposed here and there at the same general level as that of the surrounding rock. Many large lodes, however, some of them thousands of feet long, are exposed originally only at one or two places. The facility with which outcrops of ore bodies are covered up or otherwise obscured by processes of weathering is surprising. Many valuable deposits have been found by digging in the surface débris where fragments of quartz or iron oxide suggested to the prospector the presence of a deposit underneath.

The difference in the rate of erosion of the ore and country rock may under some conditions give a hint as to the relative size of the lode in depth. As a rule a deposit that varies greatly in width down the dip and is eroded much less rapidly than the country rock will decrease in width downward. On the other hand, a lode that varies in width down the dip and is eroded more rapidly than the country rock will generally increase in width downward. If the lode is very resistant and the country rock easily eroded, then the lode crops out above the surface, and the wider part of the lode will remain exposed for a longer period than the narrower part. Fig. 111 illustrates this case. The lode is more resistant to erosion than the country rock and crops out as a ridge. The solid line represents an erosion surface that shows a maximum amount of the hard material and may be called an "enduring" surface; the dotted line represents an erosion surface that shows a maximum amount of the soft rock and may be called a "temporary" surface. If, on the other hand, the deposit is less resistant than the country rock, the narrow portion is likely to remain at the surface longer, as shown by Fig. 112, in which the solid line represents the "enduring" outcrop, and the dotted line the "temporary" outcrop. Such a deposit is likely to increase in size as it is followed downward. In other words, a maximum amount of the most resistant material, be it ore or country rock, tends to remain longest at the surface and to monopolize the outcrop. The majority of such deposits, though not all, will increase in size with depth. Examples of large masses of quartzitic ore outcropping in limestone that are underlain by relatively small bodies of ore in limestone are common. These include some of the most notable disappointments in mining. A siliceous bedding-plane deposit in limestone may veneer a dip slope, or a saddle of quartz in limestone may occupy the entire crest of a hill and extend downward on all sides.

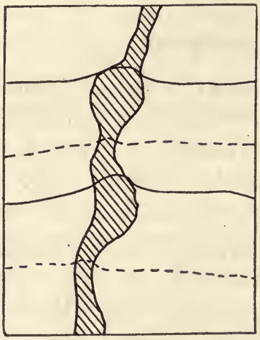

Fig. 111.—Cross-section of a lode which varies in width down the dip and which is more resistant to erosion than the country rock. The solid lines represent the "enduring" surface, the dotted lines the "temporary" surface.

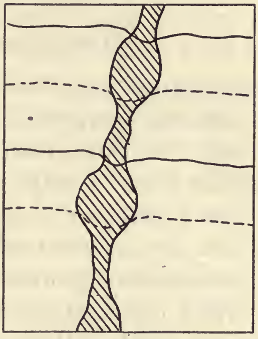

Fig. 112.—Cross-section of a lode which varies in width down the dip and which is less resistant to erosion than the country rock. The solid lines represent the "enduring" surface the dotted lines the "temporary" surface.

CHAPTER XVIII

METASOMATIC PROCESSES

Mechanism of Replacement

Metasomatism is a chemical process by which a mineral or rock is replaced by another of different composition and the form of the earlier body is preserved. The process of replacement or substitution goes on under widely varying conditions and operates in the formation of epigenetic ores of every class. It has been active in connection with the formation of some pegmatites; it is the dominant process in the formation of many contact-metamorphic ore deposits; it is operative where veins are formed by solutions, magmatic or meteoric, hot or cold, at great depths or at moderate depths or near the surface. Metasomatism is important in rock weathering, oxidation, and secondary sulphide deposition; in chalcocitization it is the dominant process. The changes, though not more clearly shown, are easier to trace in rocks and ores that have been altered metasomatically in the zone of weathering and sulphide enrichment than in rocks that have been altered at profound depths by hot solutions.

An ore undergoing surface decomposition by weathering is first attacked along small fractures or bedding planes, or wherever oxidizing solutions can make their way. In and near these openings the later secondary minerals are developed. Where the process goes on until the secondary products predominate, the original unaltered or slightly altered material will remain as nodules or irregular bodies surrounded by the secondary material. Some minerals show a very strong tendency to assume the spherical shape. Any irregularities or sharp protuberances are generally attacked first because they present greater surfaces to the decomposing solutions. The cores of unaltered original substance may become smaller and smaller until the new substance completely replaces them.

Metasomatism takes place by solution and reprecipitation in very small openings. If large solution cavities form before appreciable precipitation begins, minute textures will not be preserved, and the material undergoing alteration may collapse, so that even its form will be destroyed; but if precipitation of the new substance begins before the old substance is completely dissolved the form or texture of the old substance may be preserved. This frequently happens where the rock subjected to attack contains a radicle that unites with one present in the solution, to form an insoluble compound. In many places the zone of solution and reprecipitation is so narrow that no space between the old and new substance is seen even on close examination. In the zone of oxidation the secondary substances, such as carbonates and oxides, usually contain numerous cavities; their porous or spongy character, even in minute particles, is generally evident. At some places, where a new mineral has replaced an old one metasomatically, a thin zone occupied by a spongy mass is evident between the old and new substances. Locally, however, dense new crystals and crystalline bodies may form in the open-textured mass, which later may become completely indurated by subsequent deposition of like material.

Some specimens of altered rock, on being broken, separate on the plane of contact between the old and new minerals; others break across the contact but when boiled in a dye solution are stained along the contact, showing that there is a porous zone between the minerals which admits the dye but which is nevertheless strong enough to hold the old and new material together. Still other specimens break across the contact and show no stain after boiling with dye, even when examined with a microscope. A specimen of pyrite altering to limonite from the Southern Cross mine, Montana,[1] shows a thick shell of iron oxide surrounding the pyrite and penetrating it along fracture planes. So dense is the iron oxide that no open spaces were observed under the microscope; the specimen was not stained on boiling with dye; yet it was evidently undergoing oxidation—a process necessitating the entrance of oxygen and the escape of a solution containing a sulphur compound.

In metasomatic replacement reprecipitation generally succeeds solution so closely that they seem to be essentially parts of a single process. The absence of microscopically visible spaces in many altered rocks has led to the statement, frequently made,

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[1] Emmons, W. H., and Calkins, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, p. 185, 1913.

that the new substance has replaced the old "molecule by molecule." This expression has not been in much favor in recent years because the theory encounters chemical difficulties. Also as is evident from the following figures, there is room, even in a submicroscopic space, for myriads of molecules, involving various reactions.

	Meter
Size of subcapillary sheet opening (maximum).....	0.0000001
Size of minimum particle clearly seen by microscope	0.00000025
Size of molecule..................................	0.0000000003

Even the highest-power microscope can not detect a capillary opening of minimum size. It is possible, then, that in metasomatic processes material is transferred through invisible capillary openings. The sizes stated above, moreover, are at ordinary temperatures and pressures. Under high pressures and at higher temperatures water moves through minute openings with greater freedom. Molecules have about one eight-hundredth the line dimensions of the smallest particle ordinarily visible through the microscope. Evidently the most complicated chemical reactions, involving solution and reprecipitation by stages, may be carried on in a zone so thin as to be invisible even microscopically.

When hot waters circulate along fissures and deposit ore in them they alter the wall rock of the fissures. Such hydrothermally altered rock may be noted along essentially all veins deposited by hot solutions. All rocks are affected—limestones, shales, sandstones, and igneous rocks. The nature of the changes depends upon the character of the rocks involved, the extent of their fracturing, the length of time the solutions remain active, and the temperature, pressure, and composition of the solutions. Many examples are known of rocks which have been completely replaced. Limestones, shales, and igneous rocks may be entirely replaced by silica or by silica containing various sulphides and other minerals. Again, the changes may be relatively very slight. In an igneous rock—for example, in granite—magnetite may alter to pyrite, mica may alter to chlorite, the feldspars may become but slightly clouded by the development of felty white mica (sericite), and quartz may remain essentially unchanged. All gradations exist between the two degrees of alteration, and the country rocks along some veins show them all—intensely silicified rock close to the fissure passing gradually outward through slightly altered rock into the fresh or unaltered rock. Along some veins and especially along some thin veinlets the zone of alteration is only 2 or 3 inches wide, or even less; along others it is many feet wide; and along wide zones of shattered rock, filled with closely spaced veins, the zone of alteration may be measured in hundreds of feet.

In hydrothermally altered rocks nodules of the original substance surrounded by the altered material are less common than in oxidized ores. The thermal solutions have apparently more thoroughly permeated the rocks. The changes are selective, for the belt between altered and unaltered rock comprises (1) a zone in which nearly all the minerals are hydrothermally altered, (2) a transition zone in which only certain easily altered minerals are changed, and (3) a zone composed of relatively unaltered rock. This arrangement is quite different from that of pyrite altering to limonite around the borders and in cracks of pyrite nodules, for in hydrothermal alteration the new mineral is developed at many points in the older mineral. The hot solutions appear to be capable of penetrating the rocks along the contacts and cleavage planes of minerals. One mineral may be replaced completely, while surrounding minerals may be only partly changed. The changes are such that the border of the older mineral often is easily recognized, even where replacement is complete. The chemical changes involved are solution of the older mineral and precipitation of the new one, one process following the other so closely that the texture of the old substance is preserved. When the changes begin the fresh rock may contain very little pore space, but as alteration proceeds the pore space is increased and solutions can therefore enter more and more readily the rock that is being altered.

A specimen of fresh granite after being dipped in red dye may be washed almost clean. When broken open it is seen that the dye has scarcely penetrated the rock. Even after boiling the color has not entered far. Hydrothermally altered rocks, on the other hand, are generally very porous. When a specimen of such a rock is dipped in dye it instantly becomes colored and the dye penetrates deeply.

In a rock undergoing hydrothermal alteration solution and reprecipitation take place in very minute, mainly submicroscopic spaces. But the solutions thoroughly permeate the rock and attack it at a great number of points, so that the alteration is more nearly uniform than in the nodular oxidation above mentioned. In neither process, however, are solution cavities developed that are large enough to permit slumping or the breaking down of the original bodies. In metasomatic or pseudomorphic alteration, even when the original material is completely removed and new material substituted for it, the change is accomplished little by little and the original texture remains. That is, reprecipitation follows solution so closely that the rock, although porous, is strong enough to prevent slumping. If the cavities are large enough to weaken the rock structure sufficiently, collapse of the older rocky material will result.

Where rocks are altered by contact-metamorphic processes an altered belt of the intruded rock may surround the intruding body. Generally this belt is not continuous but is developed only where solutions from the intruding rock were more active, owing to the character of the material intruded. Limestones and calcareous shales are most readily altered, but quartzites and other rocks are affected also. The zones of metamorphic alteration are not confined to rocks along fissures, and generally there is no evidence of extensive fissuring. The solutions, which were probably at high temperature and under high pressure, seem to have entered minute openings such as joint cracks and probably intergranular spaces and cleavage cracks. They appear to have soaked into the rock rather than to have circulated along master fractures, as when veins are formed. Close study of contact-metamorphosed rocks in thin section rarely shows zonal arrangement like that observed where sulphides change to sulphates or to oxides—that is, the original minerals are not surrounded by rims of the new minerals, as is common in weathering. A metamorphosed limestone may contain much of its original calcium carbonate as calcite or original silica as quartz, intergrown intimately and irregularly with the substances introduced by solutions, such as pyrite and magnetite. The entire mass has crystallized together—new substances and old. An impure limestone containing clay bands may show, on being altered, a segregation of new aluminum minerals, such as andalusite and augite, along the former clay bands, indicating that much aluminum remained there, but if the rock is thoroughly permeated by the solutions and recrystallized there are rarely nodules of clay substance surrounded by zones of andalusite or other aluminous silicates. Although the replaced rock appears to have been thoroughly permeated by the solutions, it appears not to have broken down into a pasty mass, for there is rarely a mingling of the intruded and intruding material. The changes probably go on by solution and reprecipitation, as in the simple process of weathering. Contact-metamorphic ore is not so highly porous as hydrothermally altered granite. When soaked in colored water it does not become stained so readily except along calcite cleavage planes. The massive garnet and other heavy silicates commonly formed during contact metamorphism are relatively impervious except where they are shattered as by the blow of a hammer. The solutions evidently enter between grains and along the cleavage planes, especially along those of calcite.

CRITERIA FOR RECOGNITION OF REPLACEMENT DEPOSITS

General Features.—A replacement deposit[1] is one formed by metasomatism. Replacement veins are veins along which the wall rocks are replaced by vein matter (Fig. 113). Where veins

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Page 223, transfer descriptions of figures 113 and 114.

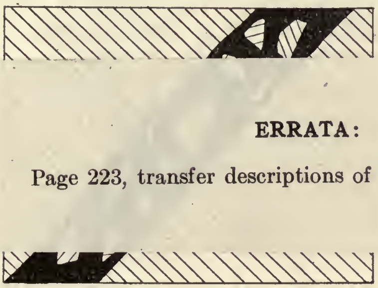

FIG. 113.—Vein formed by replacement, showing inclosed fragments whose structure is oriented like similar structure in wall rock.

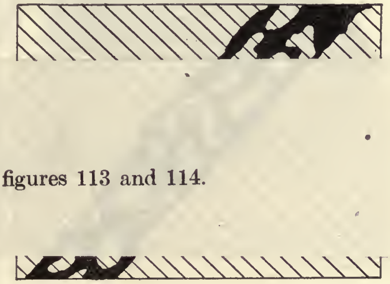

FIG. 114.—Vein filling a fissure, showing inclosed fragments whose structure is oriented unlike similar structure in wall rock.

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[1] CURTIS, J. S.: Silver-lead Deposits of Eureka, Nevada. U. S. Geol. Survey *Mon.* 7, pp. 93–106, 1884.

EMMONS, S. F.: The Genesis of Certain Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 15, pp. 125–147, 1887. Structural Relations of Ore Deposits. *Idem*, vol. 16, pp. 804–839, 1888.

LINDGREN, WALDEMAR: Metasomatic Processes in Fissure Veins. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 578–692, 1900. The Nature of Replacement. *Econ. Geol.*, vol. 7, pp. 521–535, 1912.

IRVING, J. D.: The Formation of Ore Bodies by Replacement and the Criteria by Means of Which They May Be Recognized. Canadian Min. Inst. *Quart. Bull.* 17, pp. 3–79, 1911; also in BAIN, H. F., and others: "Types of Ore Deposits," pp. 220–298, San Francisco, 1911.

are formed by hot waters, the country rock along the vein fissures is generally altered, but it is not always replaced by ore. Commonly the wall rock appears to have behaved as a semipermeable septum, for the material added to the wall rock and that precipitated in the vein are chemically different. Some of the substances in the solutions penetrate the wall rock and some remain in the open spaces. The metalliferous solutions may not penetrate the wall rock in noteworthy amounts or convert it to ore; the wall rock may be changed so little that its contacts with the fissure filling are sharp.

Pseudomorphs.—A pseudomorph is a mineral or group of minerals having the crystal form of another mineral of different composition. Pseudomorphs are developed by metasomatism and are regarded as proof of metasomatic alteration. The term "pseudomorph" has been expanded to include forms other than those of minerals. Remains of plants or animals or any bodies of characteristic shape become pseudomorphs after alteration of the material if the original shape is preserved. In many replacement deposits the larger crystals of the original rock are replaced by many smaller crystals, and the new crystals are grouped within the outlines of the older crystals so that the outlines are clearly shown. The new minerals may be developed in different proportions in the spaces formerly occupied by the older minerals, so that the details of the texture of the older rock may be seen in the new rock. The larger features of an older rock, such as jointing or sheeting, may be preserved in the rock that replaces it. In replaced sedimentary rocks bedding and jointing may be preserved. In some bodies of vein matter replacement has been complete, even the last evidence of the original rock texture being destroyed. In many places, however, there is between the massive vein material and the country rock a less intensely altered zone in which the texture of the original rock is preserved. Pseudomorphism (Fig. 115), or the preservation of ancient structure, is in itself evidence that the volumes of

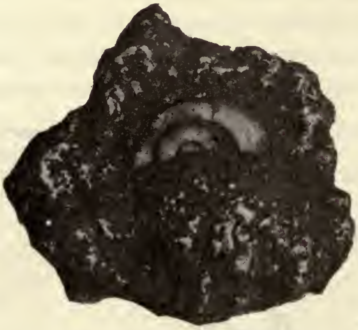

Fig. 115.—Fossil shell replaced by native silver. (*After Spurr, U. S. Geol. Survey.*)

old material are essentially unchanged. Much shrinkage or expansion would alter or destroy the structure or render it indistinct.

Banding and Crustification.—Some replacement deposits show banding, especially where the replaced rocks were banded shales or impure limestones. Banding[1] is not unknown also in normal limestone that is replaced, although it is less common. Homogeneous igneous rocks that are hydrothermally altered also may show banding. Deposits formed in open spaces are much more commonly banded than deposits that have replaced homogeneous rock. Banding is developed also during weathering (Fig. 116). Symmetrical crustified banding is not developed by replacement.

Cavities.—Large cavities are rarely found in replacement deposits, except in the superficial zone. Veins that fill fissures very commonly contain many open spaces. Thus a crustified vein generally contains many elongated vugs, and these tend to be oriented in lines or with their longer axes approximately parallel to the plane of the vein. Such an arrangement of vugs is rare in deposits that replace the country rock.

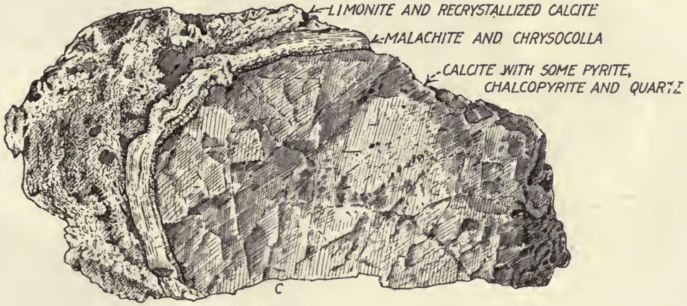

FIG. 116.—Section of partly oxidized ore, Apache No. 2 district, New Mexico. (*Redrawn from colored plate by Lindgren, Graton and Gordon, U. S. Geol. Survey.*)

Crystal Boundaries.—Minerals that fill fissures may form imperfect crystals, the ends that are attached to the walls being poorly developed.[2] Crystals of certain minerals that have been deposited by replacement of the wall rock may have sharp boundaries, all sides being completely shown (Fig. 117). Some species

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[1] LINDGREN, WALDEMAR: Processes of Mineralization and Enrichment in the Tintic Mining District. *Econ. Geol.*, vol. 10, p. 231, 1915.

LIESEGANG, R.: "Geologische Diffusionen," p. 83, 1913.

[2] IRVING, J. D.: Some Features of Replacement Ore Bodies and Criteria by Which They May be Recognized. *Econ. Geol.*, vol. 6, pp. 527–561, 1911.

are commonly developed in great perfection. In the following list of minerals[1] that are commonly formed by replacement those named first are more likely to be developed with good crystal outlines: Rutile, tourmaline, arsenopyrite, pyrite, magnetite, barite, fluorite, epidote, pyroxene, hornblende, siderite, dolomite, albite, mica, galena, sphalerite, calcite, quartz, orthoclase. Some other minerals, like chalcopyrite, sericite and some chlorites, very rarely show crystal outlines, even under the microscope.

Boundaries of Deposits.—Replacement deposits are more irregular in outline than veins filling fissures (Figs. 113, 114). Veins may narrow to thin sheets or swell to broad masses, but normally the changes are gradual. A replacement deposit, on the other hand, may become very thin at one place and swell abruptly at another, so that the entire deposit may be a chain of large ore bodies connected by thin seams of ore, rather than a tabular and nearly uniform mass. Some replacement deposits, however, are fairly uniform in width.

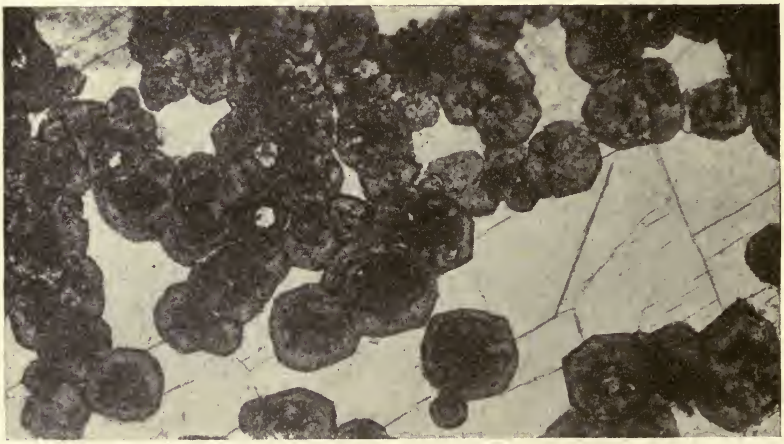

FIG. 117.—Garnet including and intergrown with cupriferous pyrite in calcite; in limestone subjected to contact metamorphism. From 1,600-foot level of Ontario mine, Park City, Utah. (*After Boutwell, U. S. Geol. Survey.*)

Contacts.—Replacement deposits generally grade into the country rock. In some deposits, especially those of copper, gold, or silver in igneous rocks, the change from ore to country rock is so gradual that the boundary of the ore body can be determined only by assays. On the other hand, in some replacement deposits

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[1] LINDGREN, WALDEMAR: "Mineral Deposits," p. 158, 1913.

the ore may grade into country rock through a zone less than 1 inch wide, and in limestone the contact between mineralized and unmineralized rock may be abrupt.

Fragments.—Small irregular fragments included in fissure fillings are likely to have sharp outlines. They are generally altered somewhat by the vein-forming solutions, but as a rule their original shape is still clearly shown. On the other hand, fragments included in replacement deposits may be rounded somewhat by solution, especially on their edges that are most exposed. This criterion, however, should be applied with caution, for in the course of deposition of a vein, solutions frequently change, and many veins during the process of deposition are opened again and again. At one period of deposition the solutions may be actively replacing the wall rock, whereas at another period their action may be more feeble. Thus, in a deposit formed principally by replacement, sharp, angular fragments of wall rock may still remain if they were broken from the walls after the solutions that were most active in replacing the wall rock ceased to be effective, and before the solutions that filled openings had ceased to deposit ore. In a small deposit in Elko County, Nevada, unaltered angular fragments of limestone are inclosed in a large body of quartz that had been deposited principally by the replacement of the limestone. In some replacement veins larger fragments that were probably surrounded by minute fragments still retain their shape, but the minute fragments appear to have been almost obliterated. Veins in siliceous sedimentary rocks and in igneous rocks more commonly contain fragments of the wall rock with sharp boundaries than veins in limestone.

Orientation of Fragments.—Near the border of a replacement deposit the rock that has been replaced may have distinctive features of structure such as bedding planes or parallel planes of schistosity. Fragments included in the replacement deposit may have similar features. If these are similarly oriented and oriented like the corresponding features in the country rock, it is a natural inference that the material surrounding them was formed by replacement (see Fig. 114), for some of them would probably have been rotated had they been broken from the parent mass by movement (see Fig. 113).

Variations in Width Depending on Country Rock.—Some replacement deposits lie with the beds (Fig. 118), others cut across them (Fig. 119). Where a replacement vein in sedimentary rock cuts across several beds of different composition, there is generally selective replacement. Siliceous or shaly beds may be only slightly changed, whereas the calcareous members may be extensively replaced. The deposit may be wider in shale than in quartzite, and still wider in limestone than in shale. In the Philipsburg quadrangle, Montana, the same system of fissures cuts granite, limestone, and shale. The deposits in granite are fissure fillings; those in limestone and shales are replacement veins. In that district some veins are very much wider in limestones than in shales. In the Black Hills, South Dakota, quartz veins cross thin beds of dolomite that alternate with shale. Where the fissures cross the more soluble dolomite strata the dolomite may be

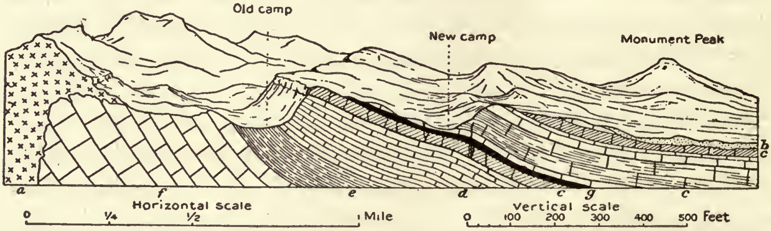

FIG. 118.—Section across Lake Valley district, New Mexico. *a*, Rhyolite; *b*, andesite; *c*, Lake Valley limestone; *d*, *e*, Percha shale; *f*, Mimbres limestone; *g*, ore horizon. (*After Endlich.*)

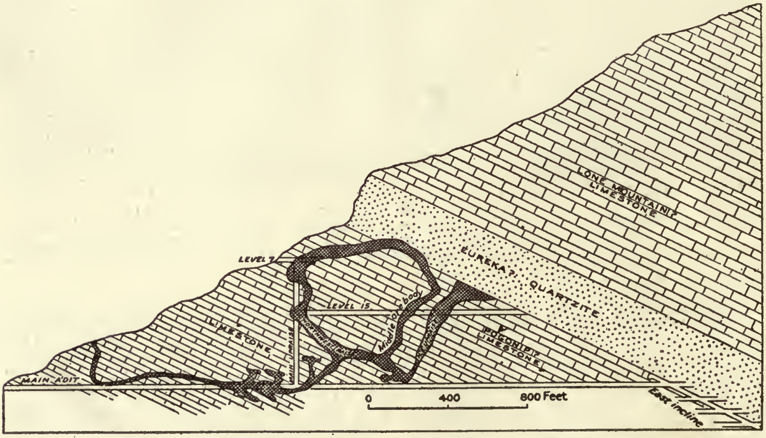

FIG. 119.—Section through Tenabo Peak, Nevada, showing irregular deposit replacing limestone at Garrison mine.

replaced so extensively that the bedding-plane deposits become much larger than the deposits filling the fissures (see Fig. 120). Thus some veins may grade into bedding-plane or irregular replacement deposits, and in limestone such gradations are very common.

Residual Minerals.—Some rocks that are replaced contain small amounts of minerals that resist replacement processes.

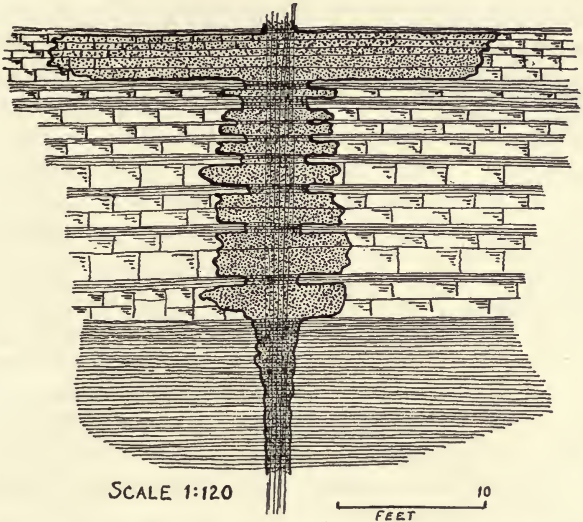

Fig. 120.—Cross-section of ore shoot in alternating layers of shale and dolomite, Portland, South Dakota. In the dolomite the ore runs out to greater distances than in the shale. (*After Irving.*)

Under some conditions apatite and zircon are but little altered by solutions that replace rocks containing them. If approximately equal quantities of these resistant substances are found in ore and country rock, the inference is warranted that the deposit has replaced the wall rock.

CHAPTER XIX

MINERAL ASSOCIATIONS IN VEINS AND WALL-ROCK ALTERATION

Basis of Classification.—It is not everywhere possible to distinguish vein matter which has filled open spaces from that which has replaced the wall rock, and it is impracticable to discuss one without the other. By comparing the unaltered country rock with the altered rock along the veins to ascertain the nature of the changes, it is possible to estimate the material added and that removed by the vein-forming solutions. Knowledge of the results of the activities of vein-forming solutions affords some basis for inference concerning their composition and character. Igneous rocks in general are more nearly uniform in composition than sedimentary rocks, and slight changes in them are more easily followed. Detailed investigations of these changes have been made in many districts, and certain types of alteration have been found to be common. The method followed is to compare the chemical analysis of the unaltered rock with that of the altered rock and to compare the mineral analyses obtained by study of corresponding thin sections of the rocks. Valuable data may be obtained by estimating the mineral composition from the chemical analyses.

As igneous rocks may be grouped in various classes, according to their chemical and mineral composition—granites, diorites, gabbros, etc.—so veins may be classified according to their mineral composition and the nature of the alteration of their wall rocks. Veins are not so nearly uniform in composition as many

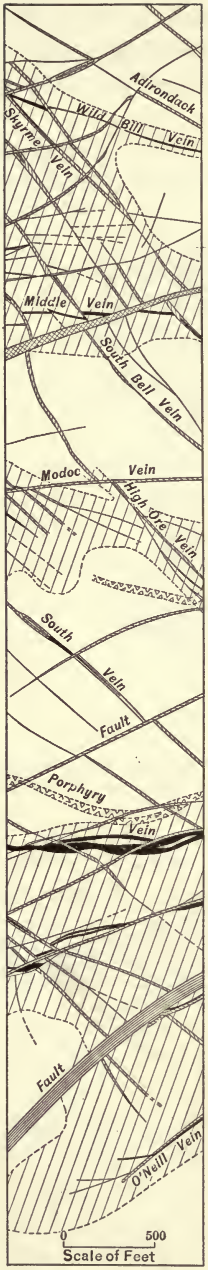

FIG. 121.—Plan of part of Butte district, Montana, showing Butte granite hydrothermally altered near veins, altered areas are cross lined. (*After Sales.*)

masses of igneous rocks, and the classes are not so sharply defined; nevertheless, for purposes of study and comparison a grouping according to mineral composition is useful. Some mineral associations in ore deposits are fairly common, especially in deposits formed within a single metallogenic epoch. Earlier investigators laid considerable stress upon mineral associations such as those of the "baritic lead veins," the "fluoritic gold-quartz veins," "pyritic gold-quartz veins." Subsequent developments and investigations have shown that these associations are not so nearly standard as they were once supposed to be. There are nearly 200 common ore and gangue minerals, and many types of ores result from combinations of them. Within a single district indeed, in a single deposit, even the unaltered ore may show great variations in mineral composition. There are, nevertheless, certain combinations that are so common as to merit special consideration. The types of wall-rock alteration are more nearly standard and may be reduced to fewer groups. As the mineral composition depends on conditions usually related to the depth of formation[1] the classification here adopted

	Tufa.
DEPOSITS FORMED AT ORIFICES OF HOT SPRINGS	Sinter.
	Travertine.
	Baritic fluorite veins.
	Zeolitic native copper veins.
	Chalcedonic cinnabar veins.
DEPOSITS OF SHALLOW ZONE	Alunitic kaolinic gold veins.
	Fluorite-tellurium-adularia veins.
	Gold-silver-adularia veins.
	Propylitic veins.
	Sericitic silver-gold veins.
	Sericitic copper veins and disseminated sericitic copper ores.
DEPOSITS OF ZONE OF MODERATE DEPTH	Sericitic copper-silver veins.
	Sericitic zinc-silver veins.
	Sideritic lead-silver veins.
	Sericitic calcitic gold veins.
	Tourmaline-gold veins.
DEPOSITS OF DEEP ZONE	Tourmaline-copper veins.
	Cassiterite veins.
	Garnetiferous lead-silver veins.
	Garnetiferous silver-copper veins.
	Garnetiferous gold veins.

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[1] LINDGREN, WALDEMAR: The Relation of Ore Deposition to Physical Conditions. *Econ. Geol.*, vol. 2, pp. 105–127, 1907.

EMMONS, W. H.: A Genetic Classification of Minerals. *Econ. Geol.*, vol. 3, pp. 611–627, 1908.

may be regarded as a refinement of the classification of primary veins presented on pages 49–73. Typical examples are cited below, and a summary of their general occurrence is given in the foregoing list, in which the arrangement indicating depth applies only to the four main groups, not to the subgroups.

Garnetiferous Gold Veins.—Precious-metal deposits with a garnet gangue are not common, but several examples are known. At Dahlonega, Ga.,[1] in a region of mica schists and amphibolites, garnetiferous gold lodes are numerous and extensive. Near the gold deposits, which occur as veins and irregular lenses, the schists are intruded by granite. In some of the deposits the ore is banded and consists of garnet, quartz, dark mica, and amphibole, the sulphides including pyrite, pyrrhotite, chalcopyrite, and galena (see Fig. 52). Fluid inclusions containing gas bubbles and a solid are abundant. The deposits, according to Lindgren, were probably formed 15,000 or 20,000 feet below the surface and at high temperatures and pressures. Garnet is a gangue mineral in gold quartz veins of Pinetuckey, Ala.[2]

Garnetiferous Silver-copper Veins.—Silver lodes containing garnet are rare but not unknown. Such deposits are found in Rossland, British Columbia,[3] in the Trail Creek district, a short distance north of the international boundary. The rocks exposed include Carboniferous limestone, quartzites, and shales with interbedded tuffs, ash beds, and lavas. Above this series are volcanic agglomerates and lavas. These rocks are intruded by masses of monzonite, granodiorite, nepheline syenite, etc.

The principal deposits are fissure fillings and replacement veins, deposits in fractured zones, and disseminated deposits The most important lodes have steep dips. The deposits carry commercial amounts of copper and silver. The gangue minerals are biotite, quartz, calcite, tourmaline, amphibole, chlorite, and garnet; the sulphides include pyrrhotite, chalcopyrite, pyrite, arsenopyrite, marcasite, and other minerals.

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[1] LINDGREN, WALDEMAR: The Gold Deposits of Dahlonega, Georgia. U. S. Geol. Survey *Bull.* 293, p. 119, 1906.

[2] MCCASKEY, H. D.: Notes on Some Gold Deposits of Alabama. U. S. Geol. Survey *Bull.* 340, p. 46, 1908.

[3] DRYSDALE, C. W.: Geology and Ore Deposits of Rossland, British Columbia. Canada Geol. Survey *Mem.* 77, 1915.

Garnetiferous Lead-silver Veins.—At the St. Eugene mine, Moyie, British Columbia,[1] one of the greatest lead mines of Canada, the deposits are lodes of the deep vein zone. The ore bodies are associated with the massive purer quartzites of the Purcell series. The ore consists of galena, both fine and coarse grained, associated in places with zinc blende, pyrrhotite, and magnetite. The gangue, which is in small amount, consists of garnet, actinolite, and a little quartz. Locally the wall rock in the immediate vicinity of the ore bodies shows strong metamorphism and development of garnet and anthophyllite.

Cassiterite Veins.—Nearly all tin veins are associated with granitic intrusive rocks. They are found in granite or near granite contacts in rocks which the granite intrudes. Almost everywhere in the veins some or all of the following minerals are associated with cassiterite: Topaz, tourmaline, muscovite, fluorite, wolframite, scheelite, lepidolite, zinnwaldite, arsenopyrite, and apatite. These minerals are deposited in openings and replace the country rock.[2]

The largest deposits of lode tin are those of the Cornwall peninsula, England (Fig. 222), an area of Paleozoic sedimentary rocks and lava flows, with subordinate crystalline schists, intruded in post-Carboniferous time by large masses of granite, some of which have outcrops over 10 miles in diameter. The tin and copper lodes are in or near the granite, and some of them are associated with dikes of quartz porphyry. Some of the lodes are mere cracks not more than an inch wide, but others are of great width and contain much crushed or brecciated material. Fissures and sheeted zones are filled with ore, which also replaces the walls and included fragments.

The most valuable deposits are those in the brecciated zones, some of which are extensive. The Dolcoath lode is 3½ miles long and has been worked through a vertical range of over 3,000 feet. The lode ores include cassiterite, stannite, chalcopyrite, arsenopyrite, wolframite, scheelite, and compounds of cobalt, nickel, and bismuth. The gangue minerals include quartz, tour-

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[1] Schofield, S. J.: Reconnaissance in East Kootenay. Canada Geol. Survey *Summ. Rept.* for 1911, pp. 158–164, 1912. The Origin of the Lead-Silver Deposits of the East Kootenay, British Columbia. *Econ. Geol.*, vol. 7, pp. 351–362, 1912.

[2] Ferguson, H. G., and Bateman, A. M.: Geological Features of Tin Deposits, *Econ. Geol.* Vol. 7, p. 209, 1912.

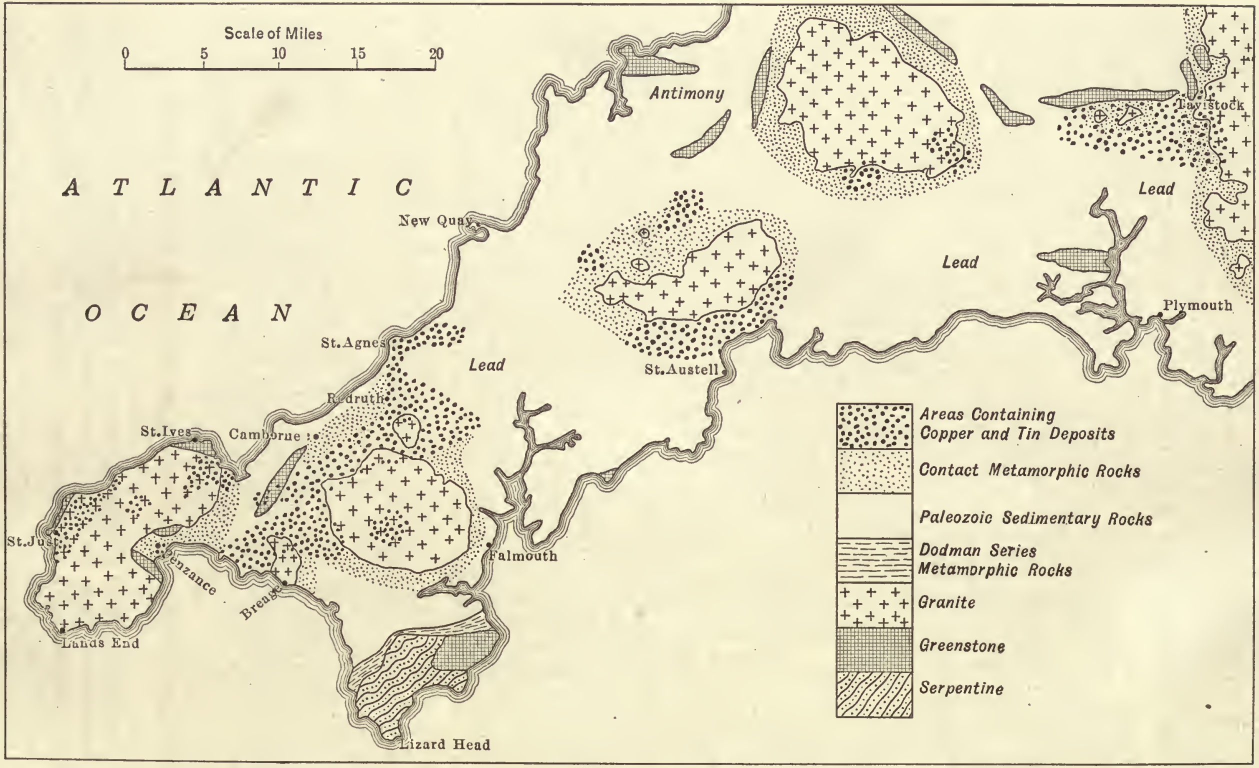

FIG. 122.—Geologic map of Cornwall region, England. (*Based on map by MacAlister.*)

maline, topaz, fluorspar, and chlorite. The secondary minerals include cuprite, melaconite, copper, malachite, chrysocolla, etc.

Near the veins, according to MacAlister,[1] the granite has undergone the following changes: Feldspar is converted into lepidolite (gilbertite), hydro-muscovite, tourmaline, topaz, fluorite, chalcopyrite, and cassiterite. The biotite of the granite is bleached or hydrated or converted into brown tourmaline. The original quartz of the granite is not greatly changed, but some is corroded. The dissolved silica, with that resulting from the altered feldspar, is deposited elsewhere as quartz. The altered granite is termed "greisen."

Near the contact the sedimentary rocks are locally impregnated with ore, and the hydrothermal alterations related to the veins may be superimposed upon contact-metamorphic alterations. In the argillaceous bands tourmaline is extensively developed, with andalusite, cordierite, and other minerals; in the calcareous bands and in greenstones axinite, pyroxene, epidote, and garnet are developed and tourmaline is subordinate.

The solutions contained fluorine, boron, sulphur, silica, lithia, water, and perhaps chlorine and carbon dioxide. The probability that they withdrew from the magma as it crystallized was suggested by Daubrée and Élie de Beaumont, and this view is supported by the recent work of MacAlister[2] for the Geological Survey of Great Britain.

At Altenberg, Saxony,[3] a small granite stock of post-Permian age cuts through a granite porphyry. The granite stock is intersected by numerous small tin-bearing veins, and the country rock is impregnated with cassiterite and other minerals. Quartz, muscovite, lepidolite, tourmaline, and topaz are formed in large quantities and here and there completely replace the feldspars and other minerals of the granite. The altered rock (greisen) is locally called "zwitter."

Tin deposits are rare in the United States. The tin bearing pegmatites of the Carolinas and the deposit at Etta Knob, in the Black Hills, are mentioned on pages 522–524. Some tin

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[1] MacAlister, D. A.: Geological Aspects of the Lodes of Cornwall. *Econ. Geol.*, vol. 3, p. 374, 1908.

[2] MacAlister, D. A.: *Op. cit.*, p. 377.

[3] Dalmer, Karl: Der Altenberg-Graupener Zinnerzlagerstättendistrict. *Zeitschr. prakt. Geologie*, pp. 313–322, 1894.

has been found near El Paso, Texas,[1] in a post-Paleozoic granite that is cut by cassiterite veins carrying quartz and wolframite with greisen-like alterations.

Fluoritic tin veins, with tourmaline and topaz, inclosed in intruding granite, are found on Seward Peninsula, Alaska.[2]

Tourmaline Veins.—Tourmaline is developed as a gangue mineral in a considerable number of ore veins. The cassiterite ores in which it is commonly present are mentioned above. At the Cactus mine, in the San Francisco region, Utah,[3] copper ores are composed of tourmaline, anhydrite, and chalcopyrite. On Cable Mountain, near the head of Flint Creek, in the Philipsburg quadrangle, Montana,[4] veinlets of tourmaline, quartz, and native gold, with a little pyrite, occupy joint fissures in quartzite. The filled portions of these veinlets are not more than a millimeter thick, but the surfaces of some of the quartzite blocks are liberally plastered with free gold. Near the veinlets tourmaline is developed in the quartzite through replacement, but the visible gold is limited to the small spaces.

In the Meadow Lake district, California,[5] quartz-tourmaline-chalcopyrite veins, with pyrite, arsenopyrite, pyrrhotite, and zinc blende, cut granitic and dioritic rocks. Tourmaline accompanies some of the zeolitic copper ores associated with trap in New Jersey.[6] Many copper veins of Chile[7] carry tourmaline. In these chalcopyrite and pyrite are common associates of tourmaline and quartz.

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[1] Weed, W. H.: The El Paso Tin Deposits. U. S. Geol. Survey *Bull.* 178, 1901. Tin Deposits at El Paso, Tex. U. S. Geol. Survey *Bull.* 213, p. 99, 1903.

[2] Collier, A. J.: Tin Deposits of the York Region, Alaska. U. S. Geol. Survey *Bull.* 225, pp. 154–167, 1904.

Knopf, Adolph: Geology of the Seward Peninsula Tin Deposits, Alaska Geol. Survey *Bull.* 358, 1908.

[3] Butler, B. S.: Geology and Ore Deposits of the San Francisco Region, Utah. U. S. Geol. Survey *Prof. Paper* 80, p. 121, 1913.

[4] Emmons, W. H., and Calkins, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, p. 241, 1913.

[5] Lindgren, Waldemar: The Auriferous Veins of Meadow Lake, Cal. *Am. Jour. Sci.*, 3d ser., vol. 46, p. 201, 1893.

[6] Lewis, J. V.: Copper deposits of the New Jersey Triassic Econ. Geology. Vol. 2, pp. 242–257, 1907.

[7] Stelzner, A. W.: Ueber das Turmalinführung Kupfererzgänge von Chile. *Zeitschr. prakt. Geologie*, 1897, pp. 41–45.

Sericitic Calcitic Gold Veins.—The principal gold veins of California are in or near granodiorite bodies that are intruded in various igneous, metamorphic, and sedimentary rocks. The most common minerals are pyrite, chalcopyrite, arsenopyrite, galena, and zinc blende, with quartz, calcite, dolomite, and siderite. More rarely molybdenite, tellurides, tetrahedrite, cinnabar, and pyrrhotite are developed with albite, barite, and fluorite. The sulphides make up only a very small percentage of the vein stuff. Sericite and chlorite are common in the replaced wall rock. Adularia, which is frequently deposited during mineralization of the later Tertiary rocks, is probably absent altogether, and the manganese minerals rhodochrosite and rhodonite are rare if not unknown in the gold lodes. In the granodiorite near these deposits the thermal waters that deposited the ore have reduced the amounts of iron oxides, but the carbon dioxide is greatly increased. Much of the iron is redeposited as pyrite, and some as siderite. Potash is increased, and soda is removed. Silica, alumina, and some soda are deposited in the veins as quartz and albite, the latter in minor quantities.

In the Ophir district, California,[1] amphibolites intruded by granodiorite are cut by quartz veins that fill fissures from a few inches to 3 feet wide. The ore minerals are gold, electrum (a natural gold-silver alloy), a small amount of iron, copper, and arsenical pyrites, with galena, zinc blende, tetrahedrite, and molybdenite. The gangue of the filled spaces is mainly quartz with a little calcite. The amphibolite schist is a dark grayish-green schistose rock composed of hornblende, feldspar, chlorite, pyrite, and magnetite. Its analysis is given in the following table, together with that of the highly altered amphibolite schist. The chemical analyses indicate gains of lime, potash, and carbon dioxide and losses of silica and soda. In places the wall rocks carry \$2 to \$12 a ton in gold and silver. The granodiorite consists of orthoclase, plagioclase, quartz, biotite, and hornblende. The composition of the fresh rock and its altered equivalent are shown in the table below. The analyses show gains and losses similar to those in the schist. Silica was deposited, however, in the open spaces in large quantities. Lindgren attributes the mineralization to hot ascending siliceous and carbonated solutions containing the heavy metals with alkaline sulphides.

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[1] LINDGREN, WALDEMAR: The Gold-silver Veins of Ophir, Cal. U. S. Geol. Survey *Fourteenth Ann. Rept.*, part 2, pp. 243–284, 1894.

ANALYSES OF FRESH AND ALTERED WALL ROCK AT OPHIR, CAL.[1]
(W. F. Hillebrand, Analyst)

	Amphibolite		Granodiorite	
	Fresh 1	Altered 2	Fresh 3	Altered 4
SiO_2	45.56	37.01	65.54	46.13
TiO_2	1.11	0.85	0.39	0.67
Al_2O_3	14.15	12.99	16.52	15.82
Fe_2O_3	1.20	0.43	1.40	0.89
FeO	9.83	3.57	2.49	2.27
FeS_2	7.86	7.99	.....	1.61
Cu_2S	0.10	(?)	.....	(?)
Ni,Zn	Traces	Traces	.....	Traces
MnO	0.25	0.24	0.06	0.09
CaO	2.30	9.78	4.88	10.68
SrO	Traces ?	Traces	.....	Traces
BaO	Traces ?	Traces	.....	Traces
MgO	6.76	5.49	2.52	2.13
K_2O	1.18	4.02	1.95	5.30
Na_2O	1.57	0.13	4.09	0.17
Li_2O	Traces	Traces	.....	Traces
H_2O below 110°C.	0.23	0.13	.....	0.12
H_2O above 110°C.	4.84	1.92	0.59	2.42
P_2O_5	0.14	0.06	0.18	0.10
SO_3	0.03	0.04	.....	0.04
CO_2	3.04	15.04	.....	11.24
	100.15	99.69	100.73	99.68

1. Conrad claim; fairly fresh, but contains calcite and pyrite.
2. Mina Rica vein; typical altered wall rock.
3. Lincoln.
4. Plantz vein; typical altered wall rock.

Nevada City and Grass Valley[2] are among the most productive gold mining districts of California. The area includes Carboniferous metamorphosed sedimentary rocks (Calaveras) compressed into isoclines, and associated igneous rocks which are less deformed. Above these are the Mariposa (Jura-Trias) slates, with associated diabases and serpentines. These rocks also are folded and metamorphosed but were not nearly so

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[1] LINDGREN, WALDEMAR: The Gold-silver Veins of Ophir, Cal. U. S. Geol. Survey *Fourteenth Ann. Rept.*, part 2, p. 249, 1894.

[2] LINDGREN, WALDEMAR: The Gold-quartz Veins of Nevada City and Grass Valley Districts, California. U. S. Geol. Survey *Seventeenth Ann. Rept.*, part 2, p. 110, 1896.

intensely compressed as the rocks of the Calaveras formation. They were intruded, presumably in early Cretaceous time, by great bodies of granodiorite. Strong fissure veins many of them making conjugated systems, were formed after the solidification of granodiorite. The ore veins, which are genetically related to the granodiorite, were formed before the Neocene sedimentary formations and associated lavas were deposited. The richer ores carry from $10 to $20 a ton in gold, and are of higher grade than the California deposits in general. The ore minerals are quartz, calcite, chalcedony, magnesite, sericite, mariposite (chrome mica), gold, tellurides, pyrite, pyrrhotite (subordinate), chalcopyrite, galena, zinc, blende, scheelite, arsenopyrite, tetrahedrite, stephanite, and cinnabar. The metasomatic alteration of the granodiorite is similar to that at Ophir described above. The analyses of fresh and altered rock are given in the subjoined table. The

Analyses of Fresh and Altered Rock, Nevada City-Grass Valley Region, California

	Granodiorite		Diabase	
	Fresh 1	Altered 2	Fresh 3	Altered 4
SiO_2	66.65	56.25	51.01	45.74
TiO_2	0.38	0.25	0.98	0.36
Al_2O_3	16.15	17.65	11.89	5.29
Fe_2O_3	1.52	0.76	1.57	0.13
FeO	2.36	2.64	6.08	2.06
FeS_2	0.02	2.87	1.73[3]	0.49
Cu_2S	....	....	Trace	
MnO	0.10	None	Trace	0.26
CaO	4.53	4.46	10.36	23.85
BaO	0.07	0.03		
MgO	1.74	1.69	8.87	0.94
K_2O	2.65	6.01	0.15	1.29
Na_2O	3.40	0.30	4.17	0.11
H_2O^+ below 110°C	0.18	0.30	0.24	0.22
H_2O^- above 110°C	0.72	2.36	2.09	1.07
P_2O_5	0.10	0.21	0.17	0.07
CO_2	....	4.82	....	18.91
	100.57	100.60	99.31	100.79

[1] Near Nevada City. Lindgren, Waldemar: *Op. cit.*, p. 38.

[2] Bellefontaine tunnel. *Idem*, p. 149.

[3] Above Maryland mine. *Idem*, p. 66.

North Star mine. *Idem*, p. 149.

alteration of diabase presents some noteworthy features: the diabase of the Maryland area, Grass Valley,[1] is a dark-green rock composed of lath-shaped plagioclase, augite and hornblende, with considerable original pyrite and pyrrhotite. The altered diabase is a grayish-green rock with a fine-grained groundmass and small greenish crystals. The analyses of this rock indicate losses of considerable iron, aluminum, sodium, and magnesium and of some silica; potash, lime, and carbon dioxide have been added in notable amounts.

Mineral Composition of Altered Rock at Grass Valley, California

	Granodiorite	Diabase
Quartz	25.00	35.00
Sericite	61.46	21.20
Calcite	7.23	42.15
Magnesite	2.70	0.71
Siderite	0.58	
Rhodonite		
Rutile	0.25	0.36
Pyrite	2.87	0.50
Apatite	0.46	0.15

Sideritic Lead Veins.—The Wood River district, near Hailey, Idaho,[2] has produced much silver, lead, and gold. It is an area of Carboniferous sandstones, shales, and limestones intruded by granite (quartz monzonite), near the contact of which heavy silicate minerals are developed in the sedimentary rocks. Neocene lavas rest unconformably on the granite and older rocks. The principal deposits are replacement veins in calcareous shale and subordinately in quartz monzonite and quartz diorite. The gangue is siderite, and the chief ore mineral is galena. Other minerals are pyrite, zinc blende, arsenopyrite, and tetrahedrite, with a little quartz. The ore carries 50 per cent. of lead and from 50 to 100 ounces of silver and $2 to $5 in gold to the ton. The deposits, though smaller, are of higher grade than those of the Coeur d'Alene district. Analyses of the fresh quartz monzonite and its hydrothermally altered equivalent are given below. The

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[1] *Idem*, p. 66.

[2] Lindgren, Waldemar: The Gold and Silver Veins of Silver City, De Lamar, and Other Mining Districts in Idaho. U. S. Geol. Survey *Twentieth Ann. Rept.*, part 3, p. 211, 1900.

loss of potash is noteworthy. The table also includes analyses of the fresh and altered quartz diorite, in which the changes caused by the solutions are seen to be of the same general character.

ANALYSES OF FRESH AND ALTERED WALL ROCKS, HAILEY, IDAHO[1]
(W. F. Hillebrand, Analyst)

	Quartz monzonite Idaho-Democrat mine		Quartz diorite Crœsus mine	
	Fresh	Altered	Fresh	Altered
SiO_2	68.42	71.93	57.78	58.01
TiO_2	0.50	0.40	1.01	1.08
Al_2O_3	15.01	12.21	16.28	15.72
Fe_2O_3	0.97	0.64	1.02	0.64
FeO	1.93	2.99	4.92	3.87
CoO + NiO	None	None	0.02	None
MnO	0.06	0.18	0.15	0.17
CaO	2.60	2.59	6.65	2.15
SrO	0.03	None	0.07	None
BaO	0.12	Trace	0.12	Trace?
MgO	1.21	0.58	4.60	2.07
K_2O	4.25	3.29	2.22	4.79
Na_2O	3.22	0.23	3.25	0.10
Li_2O	Trace	Trace	Trace	Trace
H_2O below 105°C	0.54	0.37	0.34	0.31
H_2O above 105°C	0.73	2.06	0.92	2.71
P_2O_5	0.13	0.10	0.30	0.31
CO_2	0.20	1.95	0.15	2.86
S	0.02	0.18	0.02	1.25
Fe	....	0.13	....	1.52
Co + Ni	....	None	....	0.12
Zn	....	0.09		
Pb	....	Trace	....	0.86
Cu	....	None	....	0.05
As	....	None	....	1.65
	99.95	99.92	99.88	100.24

The Coeur d'Alene district, Idaho,[2] is an area of pre-Cambrian quartzites and siliceous slates intruded by monzonite and monzonite porphyry. The most productive deposits are lead-

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[1] LINDGREN, WALDEMAR: *Op. cit.*, pp. 219–221.

[2] RANSOME, F. L., and CALKINS, F. C.: The Geology and Ore Deposits of the Coeur d'Alene District, Idaho. U. S. Geol. Survey *Prof. Paper* 62, p. 134, 1908.

silver lodes in the siliceous sedimentary rocks. The ore minerals include galena, sphalerite, pyrite, chalcopyrite, and some argentiferous tetrahedrite and stibnite. Siderite is the most abundant gangue mineral; quartz and some barite are also present. The ore has been formed largely by replacement of the siliceous country rock along fissures. The veins have great vertical extent, and in the lower levels pyrrhotite and magnetite appear. Tourmaline and siderite are deposited in the country rock beyond the limits of ore deposition (see p. 493).

Sericitic Copper-silver and Sericitic Zinc-silver Veins.—The Butte district, Montana (see page 357), is an area of quartz monzonite ("granite") intruded by aplitic granite and rhyolite porphyry and partly covered by rhyolite. Huge east-west replacement veins traverse all these rocks except the rhyolite, and these veins are crossed by northwest replacement veins that were formed in and along fault fissures. Of the east-west lodes three systems are noteworthy. These are the Anaconda and Bell-Speculator systems, which are copper-silver veins, and north of them the Rainbow lode, which yields silver and zinc. Hydrothermal alteration[1] is extensive; nearly everywhere in the ore-bearing district the granite is slightly chloritized, and along the borders of the three great east-west vein systems and also along the northwest fault fissures the country rock is highly sericitized. Where veins are thickly spaced the sericitization locally extends over areas hundreds of feet wide, and much of the ore consists of granite impregnated by copper or zinc minerals. The ascending hot solutions first attacked augite, hornblende, biotite, and magnetite and formed chlorite, epidote, secondary silica, and pyrite. Orthoclase and plagioclase feldspars were converted to sericite and silica; chalcopyrite, enargite, and other copper minerals were formed in the granite along the copper lodes, and zinc blende with some galena along the zinc-silver lodes. Locally fluorite, rhodonite, and rhodochrosite are present in both copper and zinc lodes, but the great bulk of the altered rock

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[1] Weed, W. H., Emmons, S. F., and Tower, G. W.: U. S. Geol. Survey *Geol. Atlas*, Butte Folio (No. 38), 1897.

Weed, W. H.: Geology and Ore Deposits of the Butte District, Montana. U. S. Geol. Survey *Prof. Paper* 74, p. 87, 1912.

Sales, Reno: Ore Deposits at Butte, Montana. Am. Inst. Min. Eng. *Trans.*, vol. 46, pp. 3–109, 1913.

Kirk, C. T.: Conditions of Mineralization in the Copper Veins at Butte, Mont. *Econ. Geol.*, vol. 7, p. 40, 1912.

along both copper and zinc lodes is simply sericite with residual and secondary quartz and sulphides.

It was long believed that the earlier easterly veins were essentially free from enargite and that this mineral was developed principally in the northwesterly fault fissures, but it is now known that veins of both systems carry enargite. Sales, however, has shown that the metallization is related broadly to zones (see Fig. 123). There is a central copper zone occupying the great area of altered granite in the vicinity of the Mountain View mine, in which the ores are characteristically free from sphalerite and manganese minerals. This zone is represented by the shaded area in Fig. 123. An indeterminate zone of irregular width nearly surrounds the central copper zone; in it the ores are predominantly copper but are rarely free from sphalerite, and near the outer boundaries (*A – A* and *A′–A′*, Fig. 123), rhodonite and rhodochrosite are of common occurrence. This intermediate zone is bordered by a peripheral zone of undetermined width in which copper has not been found in large quantities. The vein filling is chiefly quartz, rhodonite, sphalerite, pyrite, and rhodochrosite. In this peripheral zone are included the manganese-silver veins of the Alice, Moulton, Black Rock, Elm Or'u,

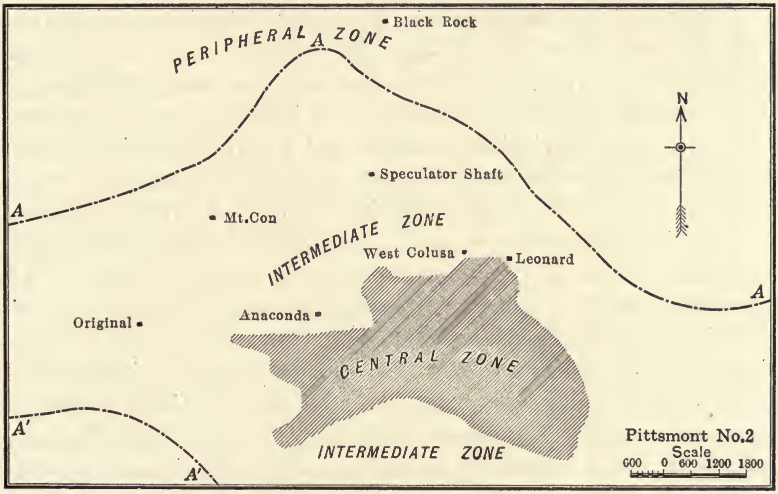

FIG. 123.—Plan of Butte district, Montana, at altitude 4,600 feet, illustrating general distribution of ore types with reference to the central copper zone. (*After Sales.*)

and Magna Charta mines, on the north, and the Emma, Ophir, Travonia, and others, on the south.

Sericitic Copper Veins and Disseminated Copper Ores.—The Clifton-Morenci district, Arizona,[1] includes pre-Cambrian granite and schists, overlain by Paleozoic and Mesozoic sedimentary rocks (page 376), which have been intruded by stocks and dikes of granitic, monzonitic, and dioritic porphyries. The contact metamorphism of the sedimentary rocks of this area and their accompanying ores are described on page 40. Great disseminated deposits of chalcocite ore are developed in the porphyry.

The following analyses and abridged notes from Lindgren's descriptions show the changes that have taken place in the porphyry as a result of hydrothermal processes. The normal fresh quartz monzonite porphyry is a light-gray rock composed of orthoclase, plagioclase, quartz, and green biotite in a microcrystalline groundmass with much quartz and orthoclase Some secondary minerals, such as sericite, epidote, chlorite, serpentine, and pyrite, are present in small amounts but do not greatly alter the composition of the rock, which is represented by analysis 1 in the accompanying table. Analysis 2 represents a specimen taken adjoining a 2-inch pyrite vein—a soft white chalky rock containing scattered pyrite and showing on a few seams a little chalcocite. The locality where this specimen was obtained is 600 feet below the surface and somewhat below the main chalcocite zone, although there is a little oxidation and chalcocitization of the vein. The rock is a felted mass of sericite with some granular quartz and is cut by veinlets of kaolin. Pyrite is present in grains and crystals. Zinc blende, chalcopyrite, and molybdenite occur in small amounts as irregular grains and aggregates; also some rutile and zircon.

Sample 3, taken about 300 feet below the surface, is a hard white porphyry with small pyrite crystals. The original structure is almost lost, but under the microscope the outlines of feldspar crystals are visible. The rock consists chiefly of a very fine sericite felt with granular quartz; the quartz also occurs as veinlets with pyrite.

Sample 4, the disseminated chalcocite ore, is a soft white chalky rock, cut by many small seams of pyrite and chalcopyrite. In

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[1] Lindgren, Waldemar: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 43, p. 168, 1905.

thin section the porphyry structure is retained, but the feldspars are entirely converted into sericite felt; the groundmass consists of granular quartz, filled with sericite. Pyrite occurs in crystals and anhedrons, largely in the altered feldspars but also with small masses of granular quartz.

Analyses of Fresh and Altered Porphyry from Mines at Morenci, Ariz.

(W. F. Hillebrand, analyst)

	1	2	3	4	5
SiO_2	68.04	46.67	69.55	64.88	72.78
Al_2O_3	17.20	20.92	16.43	16.41	15.35
Fe_2O_3	0.34	0.37	0.46	0.65	0.55
FeO	0.67	0.36	0.11		0.10
MgO	1.05	0.85	0.62	1.12	0.89
CaO	2.21	0.15	0.15	0.11	0.14
Na_2O	5.33	0.16	0.17	0.12	0.36
K_2O	2.65	4.33	5.05	4.96	5.00
$H_2O -$	0.60	0.94	1.00	0.83	1.21
$H_2O +$	1.23	5.01	2.69	2.74	3.22
TiO_2	0.41	0.43	0.41	0.38	0.45
ZrO_2	0.01	Trace?	Trace	Trace	Trace
CO_2	None	None	None	None	None
P_2O_5	0.12	0.15	0.05	0.12	0.05
SO_3	.....	0.18	0.10	0.10	0.08
MnO	0.06	None	None	Trace?	None
BaO	0.10	0.04	0.05	0.07	0.02
SrO	0.03	None	None	Trace	None
Li_2O	Trace?	Trace	Trace?	Trace	Trace
V_2O_3	Trace				
FeS_2	0.24	19.18	3.09	4.96	0.06
Cu_2S	0.02	0.24	0.07	2.42	
Zn	.....	.....	.....	None	
ZnS	0.03	0.32			
Mo	None	.....	.....	None	
MoS_2	.....	0.20	None		
	100.34	100.50	100.00	99.87	100.26

1. Fresh monzonite porphyry. Ryerson mine, first level.
2. Altered monzonite porphyry. Ryerson mine, first level; drift on Humboldt vein at end of small crosscut in foot wall 40 feet east of Humboldt claim line.
3. Altered (silicified) porphyry. Ryerson mine, intermediate level, 550 feet west of West Yankie shaft.
4. Altered porphyry within chalcocite zone. Ryerson mine, lower adit level, Humboldt vein, from stopes 70 feet wide, 80 feet above level.
5. Altered porphyry from the surface.

Sample 5 is from the surface of the northeast spur of Copper Mountain, where the rock formed brownish-gray outcrops; the porphyry structure is still visible. A thin section shows it to be an entirely sericitized rock with pseudomorphs of feldspars and biotite. The groundmass consists mainly of fine-grained quartz, with sericite foils.

The mineral components of these rocks, calculated by L. C.

Mineral Composition of Fresh and Altered Porphyry from Mines at Morenci, Ariz.

	1	2	3	4	5
Quartz	21.35	19.13	49.33	43.03	50.81
Orthoclase (mol.)	13.12				
Albite (mol.)	45.26				
Anorthite (mol.)	9.52				
Apatite	0.28	0.36	0.12	0.30	0.12
Zircon	0.02				
Magnetite	0.41				
Ilmenite	0.81				
Rutile	.....	0.43	0.41	0.38	0.45
Sericite	3.75	38.50	43.44	44.94	44.29
Kaolin	......	17.90			
Chlorite	[a]3.04				
Serpentine	[b]0.98	[c]2.81	[d]1.71	[e]2.74	[f]2.71
Epidote	[g]0.59	.....	0.43	.....	[g]0.36
Alunite	.....	0.46 (?)	0.26 (?)	0.26 (?)	0.21 (?)
Water (below 100°C.)	0.60	0.94	1.00	0.83	1.21
FeS_2	0.24	19.18	3.09	4.96	0.06
Cu_2S	0.02	0.24	0.07	2.42	
ZnS	0.03	0.32			
MoS_2	.....	0.20			
	100.02	100.47	99.86	99.86	100.22

[a] Amesite, MgO:FeO = 6:1.

[b] 0.39 per cent. MgO, 0.19 per cent. H_2O residue, with 0.40 per cent. SiO_2—too high in H_2O for serpentine.

[c] 0.84 per cent. MgO, 0.29 per cent. FeO, 0.53 per cent. H_2O residue, with 1.15 per cent. SiO_2—too high in H_2O for serpentine.

[d] 0.62 per cent. MgO, 0.39 per cent. H_2O residue, with 0.70 per cent. SiO_2 corresponds fairly well to deweylite.

[e] 1.11 per cent. MgO, 0.49 per cent. H_2O residue, with 1.12 SiO_2—too high in H_2O for serpentine.

[f] 0.89 per cent. MgO, 0.95 per cent. H_2O residue, with 0.87 per cent. SiO_2—too high in H_2O for serpentine.

[g] Al_2O_3:Fe_2O_3 = 4:1.

Graton from analyses and thin sections, are shown in the table on page 246.

This table shows the altered rocks to consist chiefly of sericite, pyrite, quartz, and serpentine. Kaolin occurs only in sample 2, the only one taken immediately adjacent to an important seam or vein. The silica has not been materially changed, except in No. 2, where it is lowered to correspond to the high percentage of kaolin and pyrite. Alumina is generally constant but has been increased in No. 2; this increase is, however, probably due to conversion of sericite to kaolin, with attendant setting free of some chalcedonic or opaline silica. MgO, TiO_2, ZrO_2, and P_2O_5 remain nearly constant. Practically all CaO and Na_2O have been carried away and FeS_2 and K_2O have been added. The alteration indicates waters deficient in carbonates but rich in potash, iron, and silica.

The Bingham district, Utah,[1] is an area of Carboniferous (Bingham) quartzite which includes numerous beds and lentils of limestone. These rocks are intruded by monzonite and monzonitic porphyries which take the form of stocks, sills, and dikes. The deposits in monzonite and monzonitic porphyry include veins and disseminated copper ores. The alterations at the Last Chance lode[2] result in decreases in calcium, sodium, and magnesium, and increases of potassium, iron, and sulphur. There is little variation in silica, alumina, and titanic oxide. The monzonite that contains the disseminated chalcocite ores is hydrothermally altered over wide areas; the alterations, so far as may be judged by microscopic studies, are similar to those at the Last Chance mine. In the fresh monzonite the chief constituents are orthoclase, plagioclase, augite, biotite, and a little hornblende and quartz. Pyrite and chalcopyrite occur sparingly on parting planes. Sericite, potash feldspar, and biotite are developed by hydrothermal alteration. The sericitized rock is crossed by numerous unsystematized fractures so closely spaced that at many places it is almost impossible to cleave a hand specimen of the usual size without breaking it along a fracture. The copper occurs in these thin crossings and is disseminated through the bleached wall rock.

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[1] Boutwell, J. M., Keith, Arthur, and Emmons, S. F.: Economic Geology of the Bingham Mining District, Utah. U. S. Geol. Survey *Prof. Paper* 38, 1905.

[2] *Idem*, p. 178.

Sericitic Silver-gold Veins.—The sericitic silver-gold veins of Granite County, Montana,[1] include several parallel lodes that are traceable for a mile or more along the strike. They cut quartz monzonite of early Tertiary age. The granite walls of the fissure fillings have not been replaced by ore to any great extent, and nowhere, so far as known, can the granite of the walls or horses be worked at a profit. The metasomatic changes which the ore-depositing solutions have produced in the granite are nevertheless noteworthy and clear in their expression. These solutions have attacked nearly all minerals in the granite and have deposited large quantities of calcite and sericite with considerable quartz. The alteration extends to varying distances, but the greatest alteration is confined to a zone less than 20 feet on each side of the vein.

Gold-silver-adularia Veins.—The gold-silver veins of De Lamar and Silver City, Idaho, are post-Miocene deposits that were formed very near the present surface. These veins are in rhyolite, basalt, and granite. The surface at the time of deposition, as shown by Lindgren,[2] was not more than 700 to 2,000 feet above the deposits mined. The gangue consists of quartz and adularia, with some chalcedony. Much of the quartz is pseudomorphous after calcite or barite. Small quantities of chlorite, epidote, barite, siderite, and calcite are present also. The ore minerals are gold, silver, argentite, proustite, pyrargyrite, polybasite, miargyrite ($AgSbS_2$), chalcopyrite, zinc blende, galena, pyrite, and a little marcasite. Some of the rich ore was formed very near the old surface and is probably primary. The analyses of the altered rhyolite show that potash and aluminum have been removed as well as soda. The removal of both the alkalies, the presence of marcasite and chalcedony, and the extensive kaolinization of the walls are noteworthy.

Chloritic Alteration in Granitic Rock.—In many metalliferous districts three principal types of alteration are recognized—chloritic alteration in a zone extending far out from the deposits, extensive sericitization within this zone, and silication near the master fractures. Where the fractures are closely spaced the

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[1] Emmons, W. H., and Calkins, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, 1912.

[2] Lindgren, Waldemar: The Gold and Silver Veins of Silver City, De Lamar, and Other Districts in Idaho. U. S. Geol. Survey *Twentieth Ann. Rept.*, part 3, p. 165, 1899.

area of sericitic alteration may be hundreds of feet wide and the chloritic alteration may extend over thousands of feet. At Butte, Mont., the chloritic alteration consists chiefly of the development of chlorite and pyrite in the iron-bearing minerals, and the clouding of feldspar by incipient sericitization. Some epidote and secondary quartz also are developed. This phase appears in practically all the granite within the mineral-bearing area at Butte. Alteration of this type is attended by relatively little addition or subtraction of material. It is believed to have been brought about by gases or by waters that deposited ore and sericitized the wall rock near the ore-bearing fissures. Although less extensive, the chemical changes brought about by chloritic alteration are chemically similar to those accomplished by sericitization.

Chloritic Alteration in Lavas (Propylitic Alteration).—In many districts, particularly in certain western camps, where ore deposits were formed in lavas during Miocene and Pliocene time, the country rock is altered over wide areas. Near the surface, rocks fracture more readily than at greater depths, because they are not held down by so great a mass of overlying rocks. Hot waters and gases ascending along major fractures spread out, entering cracks and joints and mineralizing practically the entire country rock between the veins. In such a district the rocks in an area of more than a square mile may be altered, and if the district lies in a mountain range the mineralized area may be noted by an observer miles away. Experienced prospectors appreciate the significance of the alterations, which give what some designate a "kindly look" to the rock. Andesite and basalt are generally changed to a dull green; rhyolite to a paler green and locally to a chalky white.

A common type of such alteration is the propylitic phase, in which the following changes are noteworthy: Minerals containing iron, such as hornblende, pyroxene, and biotite, are altered to chlorite, epidote, and pyrite. Glassy feldspars lose their glassy habit. A glassy groundmass is recrystallized largely to feldspar and quartz, with some chlorite, epidote, and calcite. Some sericite is nearly always developed. Chemically there is a loss of sodium and generally of alkaline earths; sulphur and water are added. These changes are very common in andesites, dacites, and basalts. In rhyolite less chlorite and more sericite may be formed, and quartz may be added in considerable quantities by the silication of iron-bearing minerals and feldspars. In many districts the alteration increases near the veins, where less chlorite is developed and more sulphides and quartz. As in granite, three types of alteration are distinguished in some districts—chloritic alteration extending over wide areas, sericitic alteration nearer the veins, and silication of the wall rock adjoining the main fractures.

Sericitic and Propylitic Alteration Compared.—Sericitic alteration and propylitic alteration are the most common types of hydrothermal metamorphism of igneous rocks near veins that are formed at moderate and at shallow depths. They are generally attended by similar chemical changes, although the changes involved in sericitization are greater. This is shown by the calculations of Reber,[1] who employed the circular diagram first used by Ransome.[2] On this diagram, reproduced as Fig. 124, are plotted 10 pairs of analyses of fresh rocks and of corresponding hydrothermally altered rocks. The 16 radii represent radicles or molecules of the analyses and are so named. The points where the radii are met by the heavy circle represent the compositions of the 10 unaltered rocks. In each corresponding altered rock the percentage losses are plotted on the 16 radii toward the center of the circle, and gains are plotted outward from the heavy line. The points showing losses or gains so plotted are connected by lines solid or broken in different ways so that changes brought about by alteration may easily be compared by following these lines around the circle. It is evident, on inspecting the diagram, that potash, and combined water, are practically always increased whether the alteration is by sericitization or propylitization, that soda and magnesia are always reduced, and that there is generally a loss of lime. Iron oxides decrease, considerable iron being changed to sulphide. Carbon dioxide is commonly added.

The propylitic and sericitic alterations at Tonopah, Nevada, have been closely studied. The Tonopah district,[3] is a fault mosaic of Tertiary eruptive rocks, probably of Miocene and Pliocene age. The first rocks erupted were andesites, and these

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[1] Reber, L. E., Jr.: The Mineralization at Clifton-Morenci. *Econ. Geol.*, vol. 11, p. 566, 1916.

[2] Ransome, F. L.: The Geology and Ore Deposits of Goldfield, Nevada. U. S. Geol. Survey *Prof. Paper* 66, p. 181, 1909.

[3] Spurr, J. E.: Geology of the Tonopah Mining District, Nevada, U. S. Geol. Survey *Prof. Paper* 42, p. 213, 1905.

were followed by rhyolites and dacites as flows, intrusives, and tuffs. The first andesite, termed by Spurr the early andesite, was followed by the later andesite, which is more basic. The principal veins were formed after the early andesite was erupted and before the later andesite and consequently do not extend into the overlying rocks. The veins were formed by hot ascending waters, chiefly through replacement along sheeted zones. The primary ores have a gangue of quartz, adularia, sericite, and carbonates and contain argentite, polybasite, stephanite, silver selenide, gold, chalcopyrite, pyrite, and some galena and zinc blende.

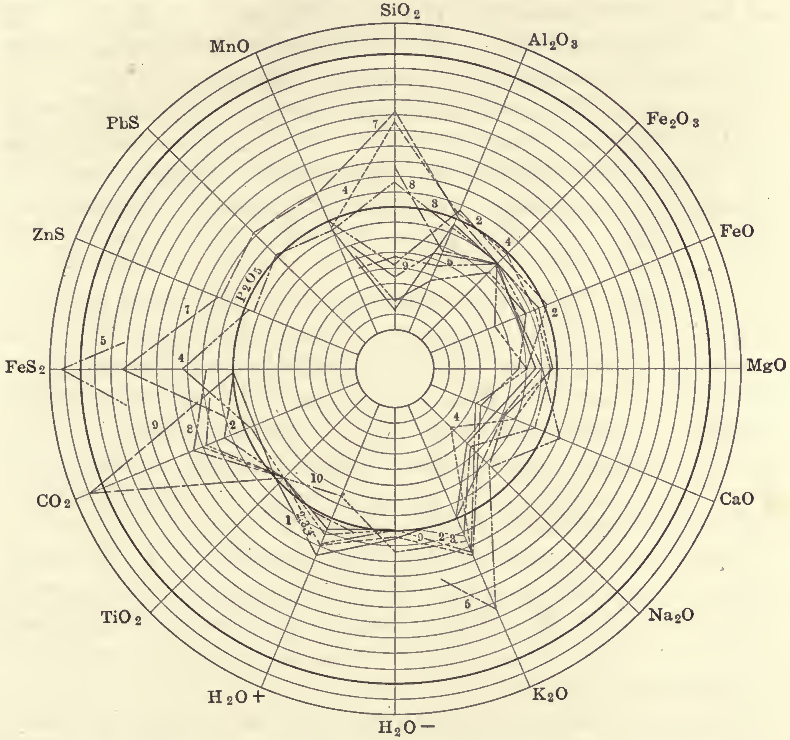

Fig. 124.—Diagram showing results of sericitization and propylitization. 1, San Francisco (Utah) monzonite, sericitic(?); 2, San Francisco monzonite, sericitic; 3, Hailey, (Idaho) diorite, sericitic and propylitic; 4, Morenci granite porphyry or monzonite, sericitic and propylitic; 5, Leadville white porphyry, sericitic and propylitic; 7, Rimini monzonite, sericite tourmaline; 8, Willow Creek (Idaho) granodiorite, sericitic and propylitic; 9, British Columbia diorite, propylitic; 10, Hauraki, (New Zealand, andesite, propylitic. (*After Reber.*)

The wall rock is greatly altered by the vein-depositing solutions. In some places the early andesite is altered chiefly to quartz, sericite, and adularia. In others it is altered chiefly by the deposition of calcite and chlorite. These phases of alteration grade into each other and were caused by the same waters. The maximum effect of these waters was the formation of the mineral veins along the major channels. Near the veins they accomplished the quartz-sericite-adularia alteration; farther away, the calcite-chlorite or propylitic alteration.

The nature of the hydrothermal alterations is shown by the table on page 254, which includes, in order, analyses representing the slightly altered chloritic or propylitic phases, the more intensely altered phases, and the highly siliceous metal-bearing phase. The following notes are abridged from Spurr's descriptions.

Specimen 1 is a dense dark-green rock obtained 670 feet below the surface. It contains small phenocrysts in a fine microlitic groundmass. Among the phenocrysts the feldspars, probably andesine-oligoclase, are prominent. They are largely altered to calcite with a little quartz. Abundant pseudomorphs after hornblende consist of dark blue-green chlorite and iron oxide. Pseudomorphs after biotite consist of fine muscovite, with a little calcite and hematite.

Specimen 2 is green but much lighter than No. 1. It shows small phenocrysts in a fine microlitic groundmass, with much felty devitrified glass. The feldspar phenocrysts (andesine), are only slightly decomposed. The ferromagnesian minerals are entirely altered.

Specimen 3, from a depth of 218 feet, is a purple rock with rather abundant phenocrysts of white andesine in a glassy groundmass. The feldspars are only partly altered to sericite; biotite has altered to muscovite, with a small amount of siderite and hematite, which forms a zone around the edge. Sericite and talc form pseudomorphs after hornblende, with inclusions and heavy rims of magnetite. Quartz forms pseudomorphs after pyroxene or biotite, with a little calcite and hematite around the borders. Other pseudomorphs consist of quartz and sericite.

Specimen 4 has a pale pinkish-purple groundmass with white phenocrysts. This shows what was originally a microlitic glassy groundmass, containing abundant secondary quartz and sericite, with limonite, hematite, and siderite. Pseudomorphs after biotite phenocrysts consist of muscovite, with a little siderite. Other phenocrysts, possibly of hornblende, are represented by pseudomorphs of quartz, sericite, and a little siderite.

Specimen 5, from the 180-foot level, near the Mizpah vein, is light salmon-pink and shows phenocrysts of feldspar, whiter than the rest of the rock. No original mineral remains. The groundmass, of which the structure may be distinguished, is altered to quartz and sericite, with a little iron oxide. The pseudomorphs after phenocrysts are well defined. Those after feldspar form aggregates of felty muscovite, with a little quartz. Those after biotite consist of muscovite, with a little siderite. Pseudomorphs after hornblende or pyroxene, or both, are barely distinguishable from the groundmass. They consist of sericite and quartz, with some siderite, which marks the outlines of the original phenocrysts. In this rock the secondary quartz varies in grain, some areas becoming more coarsely crystalline.

Specimen 6 is a hard white rock with nests of fine granular secondary adularia and quartz. The feldspar is oligoclase, mostly altered to adularia. This alteration can be seen in all stages, up to the complete pseudomorph. A little sericite accompanies the adularia. Traces of original ferromagnesian phenocrysts can be determined.

Specimen 7, from the hanging wall of the Mizpah vein, 300-foot level, is a light-gray, nearly white rock, with dull luster. It is so much altered as to be hardly recognizable and consists of an aggregate of quartz and oxidized pyrite. The quartz is segregated into little areas and veinlets. Phenocrysts of feldspar are indicated by pseudomorphous areas characterized by different groupings of the quartz and sericite; those of ferromagnesian minerals are marked by similar differences of grouping and by greater abundance of the iron minerals. The decomposition products, however, are all similar. In many areas the vestiges of the phenocrysts have been effaced.

Specimen 8 is ore material of the Mizpah vein, 300-foot level, and shows dense quartz intermixed irregularly with kaolinic material. The microscope shows fine to moderately coarse granular quartz, with much sericite. Mixed with the quartz in the finer-grained areas is adularia in crystals of characteristic rhombic section.

Spurr concludes that the mineralizing waters were charged with an excess of silica and probably of potash, together with silver,

ANALYSES OF DIFFERENT PHASES OF ALTERED EARLIER ANDESITE, TONOPAH, NEV.

	1	2	3	4	5	6	7	8
SiO_2	55.60	58.47	60.45	71.14	72.98	73.50	76.25	91.40
Al_2O_3	16.70	16.85	17.78	15.24	14.66	14.13	12.84	4.31
Fe_2O_3	2.23	2.04	5.86	1.77	1.01	1.51	0.54	0.77
FeO	3.51	3.12	0.25	0.26	0.16	0.26	0.33	0.11
MgO	2.60	3.84	1.55	0.16	0.33	0.21	0.56	0.18
CaO	4.27	1.35	1.04	0.09	0.18	0.12	0.16	None
Na_2O	4.08	4.30	3.58	0.24	None	0.24	0.12	0.06
K_2O	3.17	3.14	2.11	6.31	6.03	5.11	3.20	1.68
H_2O −	0.88	1.10	2.86	0.85	0.97	1.07	2.14	0.46
H_2O +	3.06	3.59	2.93	2.87	2.95	2.81	3.17	0.98
TiO_2	0.72	0.77	0.81	0.48	0.44	0.47	0.37	0.07
ZrO_2	Undet.	......	......	......	......	......	......	0.02
CO_2	2.76	0.52	None	None	None	None	None	None
P_2O_5	0.28	0.35	0.28	0.05	0.16	0.09	0.12	0.04
SO_3	None	None	None	0.05	......	0.17	......	None
Cl	......	......	......	......	......	......	......	None
F	......	0.12	......	......	......	......	......	Trace
S	None	......	......	0.02	......	0.03	......	None
FeS_2	......	0.49	0.06					
NiO	......	......	......	......	......	......	......	(*a*)
MnO	Undet.	0.26	(*a*)	(*a*)	(*a*)	(*a*)	(*a*)	0.06
BaO	0.12	0.11	0.07	0.17	(*a*)	0.19	......	0.02
	99.98	100.42	99.63	99.70	99.87	99.91	99.80	100.16

(*a*) Not looked for.

gold, antimony, arsenic, etc.; that they also contained carbonic acid and sulphur, with some chlorine and fluorine; but that they were noticeably deficient in iron.

Fluoritic Tellurium-adularia Gold Veins.—The Cripple Creek mining district, Colorado,[1] is an area of gneiss, granite, and schists cut by a volcanic neck composed mainly of breccia which has been intruded by syenite, latite-phonolite, phonolite, trachydolerite, and basic dikes. The ore deposits are veins or lodes and irregular replacement deposits. The ores are later than all the rocks, and there is a rudely radial arrangement of veins and dikes with respect to the center of the volcanic neck. Many of

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[1] LINDGREN, WALDEMAR, and RANSOME, F. L.: Geology and Gold Deposits of the Cripple Creek district, Colorado. U. S. Geol. Survey *Prof. Paper* 54, 1906.

the veins follow phonolite or basic dikes. The fissures are generally narrow, and much of the ore has formed through replacement of wall rock. The fissures show little pre-mineral displacement, nor are the veins extensively faulted. According to Lindgren and Ransome, the fissures were formed at about the same time as the intrusion of the basic dikes and represent a late phase of volcanic activity.

Calaverite is the chief primary constituent, and native gold is rarely present in the unoxidized ores. Pyrite is widely distributed, and galena, sphalerite, tetrahedrite, stibnite, and molybdenite are sparingly present. As gangue minerals quartz, fluorite, and dolomite predominate; celestite is common and is in many places changed to quartz. Sylvanite, krennerite, chalcedony, opal, calcite, rhodochrosite, barite, wavellite, adularia, sericite, and roscoelite are present.

The hydrothermal alteration is not intense, but in the breccia it is spread over wide areas; ferromagnesian minerals are changed to carbonates, pyrite, and fluorite; feldspar and feldspathoids are changed to sericite and adularia. Among the metasomatic minerals pyrite and tellurides are common, zinc blende rare. Sericite forms in orthoclase and is abundant in sodic minerals such as nepheline, sodalite, and analcite. Roscoelite, the green vanadium mica, is developed at some places. Adularia appears in considerable amount in the vein filling and in the wall rock. In cavities it is more abundant than quartz, which is relatively rare except where silicates have been altered. Dolomite, calcite, and some siderite have formed. Purple fluorite is widely distributed.

Alunitic Kaolinic Gold Veins.—The Goldfield district, Nev.,[1] is a low domical uplift of Tertiary lavas and lake beds that rest upon older granitic and metamorphic rocks, small areas of which are exposed here and there by erosion of the Tertiary beds. The Tertiary rocks as mapped by Ransome include rhyolite, latite, andesite, dacite, dolerite basalt, conglomerate, and tuff. The igneous rocks are mainly flows, but some are intrusive. The rocks are greatly shattered and highly altered, although the geologic structure is relatively simple. Some of the ores are in andesite, but the most productive deposits are in an intrusive dacite which probably cuts through andesite. In the sulphide

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[1] Ransome, F. L.: Geology and Ore Deposits of Goldfield, Nev. U. S. Geol. Survey *Prof. Paper* 66, 1909.

ores native gold and pyrite are accompanied by minerals containing copper, silver, antimony, arsenic, bismuth, tellurium, and other elements. In some ores the gold occurs in small particles so closely crowded together in flinty quartz as to form yellow bands or blotches. Crustification is characteristic of the richest ores, fragments of silicified, alunitized, and pyritized rock being covered by shells of gold and sulphides.

The deposits were formed near the surface, and the fissuring or fracturing is very irregular. Their age is probably Pliocene, and it is believed that the surface at the time of deposition was not more than 1,000 feet above the present surface. The minerals of the ore include alunite, barite, gypsum, kaolinite, quartz, native gold, pyrite, marcasite, tellurides, goldfieldite, enargite, famatinite, and bismuthinite. As is generally the case where ascending hot waters enter a complexly fractured zone near the surface, they have migrated far from the principal channels, and large areas are greatly altered. Over an area of several square miles fresh rocks are almost entirely lacking.

As shown by Ransome, there are three types of alteration. The less intense type is propylitic and consists of the development of quartz, calcite, chlorite, epidote, and pyrite at the expense of the rock-making minerals and the groundmass of dacite, andesite, and rhyolite.

In a second type of alteration the rock is changed to a comparatively soft light-colored mass of quartz, kaolinite, alunite, and pyrite. The quartz is flinty or cryptocrystalline. Much of the gold is associated with such alteration.

A third type of alteration is essentially similar, but the end products are more siliceous, and the materials form hundreds of craggy points and ledges that are characteristic of the topography of the district. Although most of these quartz ledges contain no ore bodies, nearly all the ore near the surface has been found in or alongside such ledges.

The alunitized area, shown in Fig. 125, is surrounded nearly everywhere by propylitic rocks. The known ore bodies are confined to the alunitic rocks but are not so widely distributed. The chemical changes are shown by the analyses on page 258. The following notes are condensed from Ransome's descriptions.[1]

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[1] Ransome, F. L.: *Op. cit.*, pp. 185–199. The Association of Alunite with Gold in the Goldfield District, Nevada. *Econ. Geol.*, vol. 2, pp. 666–692, 1907.

The fresh dacite (analysis 1) is of comparatively uniform composition. It is dark gray and contains moderately abundant labradorite phenocrysts and less numerous phenocrysts of augite and biotite with a few grains of quartz, in a dark aphanitic groundmass.

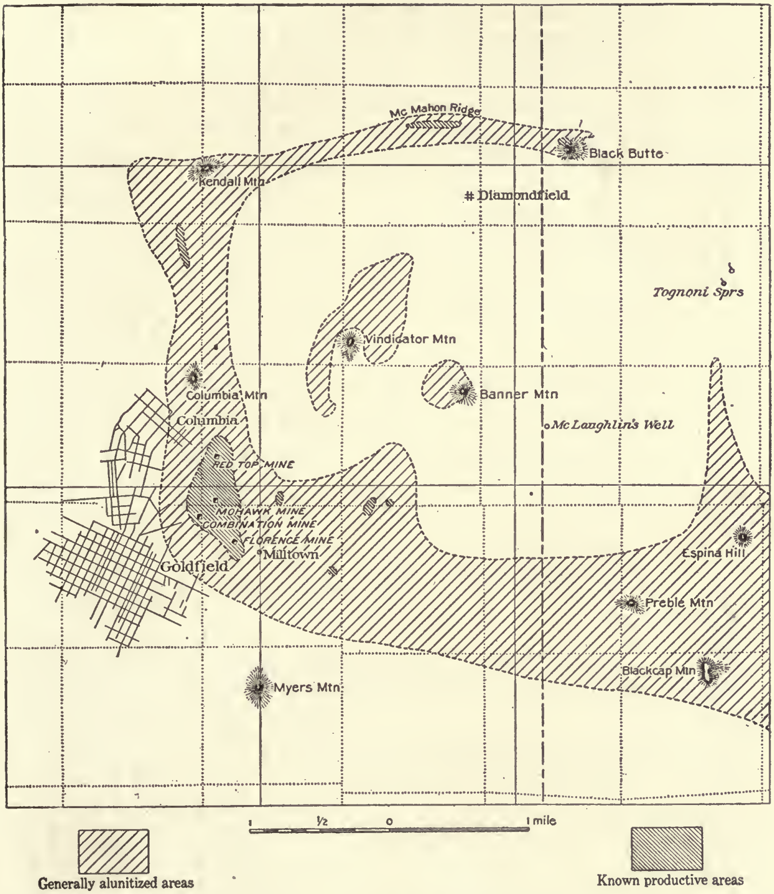

FIG. 125.—Diagram showing the portions of the Goldfield district, Nevada, in which the rocks have undergone extensive alunitic alteration. (*After Ransome, U. S. Geol. Survey.*)

In the altered dacite (analysis 2) the rock is recrystallized, with the exception of quartz phenocrysts, to an aggregate of quartz, kaolinite, alunite, and pyrite. As they stand, the two analyses show close agreement in silica, alumina, titanic oxide, and phosphorus pentoxide. When all the iron in both analyses is calcu-

ANALYSIS SHOWING CHANGES IN CHEMICAL ALTERATION OF DACITE IN THE GOLDFIELD DISTRICT, NEVADA

	1	2	1*a*	2*a*	1*b*	2*b*	1*c*	2*c*	3	4	5
SiO_2	59.95	60.53	60.86	60.75	161.52	168.04	160.07	151.27	− 8.80	−3.35	− 5.50
Al_2O_3	15.77	15.32	16.01	15.37	42.49	42.52	42.11	38.27	− 3.84	−1.46	− 9.12
Fe_2O_3	3.34	0.20	3.39	0.20	9.00	0.55	8.91	0.50	− 8.41	−3.20	− 94.39
FeO	2.34	0.14	2.37	0.14	6.29	0.39	6.23	0.35	− 5.88	−2.23	− 94.38
FeS_2	None	7.20	None	7.23	None	20.00	None	18.00	+18.00	+6.84	
MgO	2.73	0.06	2.77	0.06	7.35	0.16	7.28	0.15	− 7.13	−2.71	− 97.94
CaO	5.84	0.41	5.92	0.41	15.71	1.14	15.57	1.02	−14.55	−5.53	− 93.45
Na_2O	3.07	0.84	3.12	0.84	8.28	2.32	8.21	2.09	− 6.12	−2.33	− 74.72
K_2O	2.52	1.06	2.56	1.06	6.79	2.93	6.73	2.64	− 4.09	−1.55	− 60.77
H_2O below 110°C	0.95	1.33	0.97	1.33	2.58	3.67	2.55	3.31	+ 0.76	+0.29	+ 29.80
H_2O above 110°C	2.00	6.60	2.03	6.62	5.39	18.31	5.34	16.49	+11.15	+4.24	+206.87
TiO_2	0.82	0.80									
ZrO_2	0.02	0.01									
CO_2	None	None									
P_2O_5	0.26	0.27									
SO_3	None	5.97	None	5.99	None	16.57	None	14.91	+14.91	+5.67	
F	None	Trace									
MnO	0.09	Trace									
BaO	0.11	0.06									
SrO	0.13	Not looked for									
	99.94	100.80	100.00	100.00	265.40	276.60	263.00	249.00	−14.00	−5.32	

1. Chemical analysis of fresh dacite. George Steiger, analyst. Specific gravity of powder analyzed 2.654. Specific gravity of rock mass 2.63.
2. Chemical analysis of altered dacite. George Steiger, analyst. Specific gravity of powder analyzed 2.766. Specific gravity of rock mass 2.49.
1*a*. Analysis 1, recalculated to summation of 100, with minor constituents omitted.
2*a*. Analysis 2, recalculated to summation of 100, with minor constituents omitted.
1*b*. Constituents, in grams, in 100 cubic centimeters of fresh dacite free from pores. Specific gravity 2.654.
2*b*. Constituents, in grams, in 100 cubic centimeters of altered dacite free from pores. Specific gravity 2.766.
1*c*. Constituents, in grams, in 100 cubic centimeters of fresh dacite with 0.9 per cent. pore space. Specific gravity 2.63.
2*c*. Constituents, in grams, in 100 cubic centimeters of altered dacite with 9.9 per cent. pore space. Specific gravity 2.49.
3. Gains and losses in grams of each constituent in the alteration of 100 cubic centimeters of dacite to the same volume of altered product.
4. Gains and losses of each constituent in percentage of mass of the original 100 cubic centimeters of fresh dacite.
5. Gains and losses of each constituent in percentage of its own original mass in 100 cubic centimeters of fresh dacite.

lated as ferrous oxide, that of the altered rock shows a loss of only 0.7 per cent., so that in this respect also the two analyses are very close together. The analysis of the altered rock shows a loss of practically all the lime and magnesia, most of the soda, and one-half of the potash. It has gained much combined water, nearly 6 per cent. of sulphuric anhydride, and nearly 4 per cent. of sulphur. Such a direct comparison of analyses, while indicating in this case the general character of the change that has taken place in the dacite, is really a comparison of equal masses of the two rocks, or, strictly speaking, of the two powders as prepared and weighed for analysis.

The volumes of the rocks considered in large masses have not greatly changed, but as the fresh dacite has a porosity of 0.9 per cent. and the altered rock a porosity of 9.9 per cent., corrections are made for porosity.

In columns 1*c* and 2*c* are given the number of grams of each constituent in 100 cubic centimeters of each rock, the figures being obtained by multiplying the percentage figures in columns 1*a* and 2*a* by the respective specific gravities of the fresh and altered dacite. The gains and losses of each constituent are given in grams in column 3 and in percentages of total initial mass in column 4. Column 5 gives the percentage of loss of each constituent and displays clearly the nature of the change.

The iron has been converted to pyrite. The iron oxides in column 1*c* correspond to 11.08 grams of metallic iron; the pyrite in column 2*c* corresponds to 8.4 grams of iron and 9.6 grams of sulphur. The iron originally in the dacite was more than enough to form all the pyrite in the altered rock; the loss of iron is over 27 per cent.

The norm or theoretical composition of the fresh dacite and the mineral composition of the altered rock are given on page 260.

The agent of hydrothermal metamorphism, according to Ransome, was a strongly acid solution carrying hydrogen sulphide, sulphuric acid, and possibly sulphur dioxide, which was capable of decomposing the silicates of the dacite and carrying part of their constituents away, reacting with iron of magnetite and silicates to form pyrite, with potash and aluminum to form alunite, and with aluminum silicates to form kaolinite.

Ransome shows that the ores were probably formed by ascending hot solutions that became oxidized near the surface. The hot ascending waters carried sulphides, as shown by the exten-

NORM OF ORIGINAL DACITE

Quartz	17.34
Orthoclase	15.01
Albite	25.68
Anorthite	21.96
Zircon	0.37
Diopside	5.21
Enstatite	4.63
Magnetite	4.87
Ilmenite	1.52
Apatite	0.34
	96.93
Water	2.95
	99.88

MINERAL COMPOSITION OF ALTERED DACITE

Quartz (SiO_2)	49.38
Kaolinite ($Al_2O_32SiO_2.2H_2O$)	23.99
Alunite ($K_2O.3Al_2O_3.4SO_3.6H_2O$)	15.73
Pyrite (FeS_2)	7.20
Water (H_2O)	2.53
Other constituents	1.17
	100.00

sive change to pyrite of the iron that was originally present in the dacite and other rocks as a constituent of magnetite and silicates. This change was not confined to the rocks now alunitized but extended outward to what has been called the propylitic aureole of alteration. The changes in the dacite, notwithstanding the development of the potassium and sodium bearing mineral alunite, do not show any addition of alkalies to the original rock, but such evidence does not prove that no alkali sulphides were present in the primary solutions.

Zeolitic Native Copper Veins.—The copper deposits of Keweenaw Point, Michigan[1] extend northeastward for about 70 miles.

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[1] PUMPELLY, RAPHAEL: The Metasomatic Development of the Copper-bearing Rocks of Lake Superior. Am. Acad. Arts and Sci. *Proc.*, vol. 13, pp. 253–309, 1878.

IRVING, R. D.: The Copper-bearing Rocks of Lake Superior. U. S. Geol. Survey *Mon.* 5, 1883.

WADSWORTH, M. E.: Origin and Mode of Occurrence of the Lake Superior Copper Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 27, pp. 669–696, 1898

They are in pre-Cambrian diabasic lava and associated conglomerates which dip about 45° or less to the northwest (see page 395). The diabase is extensively fractured, and small veinlets of copper ore are commonly developed in cracks near the lodes. The larger part of the ore, however, replaces the diabase and conglomerate. The diabase lavas and conglomerates are extensively altered by hot waters. Zeolites, chlorite (delessite), epidote, laumontite, prehnite, datolite, adularia, calcite, quartz, and other minerals are developed metasomatically and also line vesicles in the lavas. Some chalcocite and bornite are found, but nearly all the copper is in the native state. A little silver is present. Alteration is more intense in the vesicular or other permeable beds. The massive centers of the great lava flows are fresh, but locally these also are crossed by small veins of native copper.

Although the deposits have been developed for about a mile below the surface, no consistent change in the character of the mineralization with increasing depth is noted. It is believed that the ores and associated minerals were formed before the beds were tilted, probably soon after the lavas were poured out (see page 399).

Chalcedonic and Calcitic Cinnabar Veins.—Nearly all quicksilver deposits, the world over, are found in areas of comparatively late igneous activity, and it is believed that all the valuable deposits have been formed relatively near the surface. In the United States the larger deposits are on the Pacific coast and in Texas (see page 499). On the Pacific coast the quicksilver ores are found in many different rocks, but the ores themselves have characteristic associations. The gangue minerals are quartz, chalcedony, calcite, barite, and gypsum. In some deposits bitumen is noted. The associated sulphides are cinnabar, pyrite, chalcopyrite, marcasite, stibnite, and realgar.

Many of the deposits are huge irregular masses formed in brecciated rock along fissures. Becker[1] termed these "cham-

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Rickard, T. A.: "The Copper Mines of Lake Superior," p. 164, 1905.

Lane, A. C.: The Keweenawan Series of Michigan. Mich. Geol. and Biol. Survey, ser. 4, vols. 1 and 2, 1911.

Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, pp. 423–426, 573–596, 1911.

[1] Becker, G. F.: Geology of the Quicksilver Deposits of the Pacific Slope. U. S. Geol. Survey *Mon.* 13, pp. 410, 472, 1888.

bered veins." The solutions depositing the ores have apparently made out from the major fractures, but the details of rock alteration by hydrothermal processes are not available.

At Steamboat Springs, Nev.,[1] on the east front of the Sierra Nevada, 6 miles from the Comstock lode, are mines that were formerly worked for quicksilver. Mercury sulphide and other minerals are being deposited there at the present day. The country rock is granite, which is cut by dikes of granite porphyry and covered locally by metamorphosed sedimentary rocks, succeeded by andesitic lavas. Hot waters issue from the granite, and a flow of basalt near the mine is altered by the waters which deposited the ore. The present vents of the springs are along a series of fissures extending for about 1 mile. Some of the openings retain their sheet-like character; others are pipe-like. The granite is highly altered and at some places silicified. Steam, hydrogen sulphide, carbon dioxide, and sulphur dioxide escape from the springs and fissures. The spring deposits contain sulphides of antimony and arsenic, ferric hydroxide, lead sulphide, copper sulphide, mercuric sulphide, gold, and silver, together with traces of zinc, manganese, cobalt, and nickel. The gangue minerals are quartz, chalcedony, opal, carbonates, sulphur, and sulphates. The temperature of the water ranges from 75°C. to 84.5°C. A sample collected by Becker

COMPOSITION OF WATER ISSUING AT STEAMBOAT SPRINGS, NEV.

	Parts per million
$FeCO_3$	0.29
$MgCO_3$	0.99
$CaCO_3$	15.77
$Ca_3P_2O_8$	1.37
KCl	97.35
Li_2SO_4	56.50
NaCl	1,414.75
NaHS	3.58
Na_2SO_4	111.47
$NaHCO_3$	290.23
Na_2CO_3	43.14
$Na_2B_4O_7$	313.68
$Na_2Si_4O_9$	390.90
Na_2SbS_3	1.00
Na_2AsS_3	8.66
Al_2O_3	0.25
$HgS.nNa_2S$	Trace

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[1] BECKER, G. F.: *Op. cit.*, p. 331.

for analysis deposited on cooling arsenic and antimony sulphides and silica on the sides of the vessel. An analysis of the water and of material deposited from it shows that its probable composition prior to oxidation was that indicated on page 262.

The springs thus offer an example of the formation of fissure veins by hot ascending waters at the present day. To ascertain the source of the metals, Becker had assays made of large samples of the granite through which the waters pass. It was found to contain small quantities of several metals but no quicksilver.

Lindgren[1] visited Steamboat Springs in 1901 and found that a shaft had been sunk 30 feet through the deposit of sinter. At a depth of 25 feet pebbles of andesite and granite were encountered, with abundant hot water. Attached to the pebbles were crystals of pyrite, stibnite, and opaline silica.

At Sulphur Bank, Cal.[2] in a region of late volcanic activity, where hot springs now issue, mercury sulphide, pyrite, and chalcedony are being deposited. The spring waters carry hydrogen sulphide, sulphur dioxide, and dissolved metals. The gases escaping at the surface deposit sulphur, which was formerly exploited.

Baritic Fluorite Veins.—Some baritic fluorite veins are formed very near the surface. Those at Wagon Wheel Gap, Colo., and at Ojo Caliente, N. Mex., described under the next heading, are formed along fissures through which hot waters now rise. These waters issue at the surface and deposit much travertine. Without much doubt these veins, like the quicksilver deposits of Steamboat Springs, Nev., and Sulphur Bank, Cal., are now in process of formation. Both barite and fluorite are formed also at moderate depths and are noted in many examples of ores described above.

Deposits Formed at the Orifices of Hot Springs.—Deposits formed at the orifices of hot springs, although of little value as sources of the metals, have great interest in connection with the genesis of metalliferous deposits, for some of them contain small amounts of the more valuable metals. At some of these springs the waters issue from fissures in which low-grade veins have

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[1] LINDGREN, WALDEMAR: The Occurrence of Stibnite at Steamboat Springs, Nevada. Am. Inst. Min. Eng. *Trans.*, vol. 36, pp. 27–31, 1905.

[2] LE CONTE, JOSEPH, and RISING, W. B.: The Phenomena of Metalliferous Vein Formation now in Progress at Sulphur Bank, Cal. *Am. Jour. Sci.*, 3d ser., vol. 24, pp. 23–33, 1882.

been deposited, without much doubt, by solutions from the sources of the waters now issuing along the fissures. Deposits formed at the orifices of hot springs are in a strict genetic sense sedimentary deposits, but they form a connecting link between sediments and epigenetic vein deposits and for that reason they are treated here. Hot springs are widely distributed. A few are found in regions of ancient volcanic activity and are doubtless fed by ground water heated while traveling a deep circuitous route through fractures or other openings in rocks. By far the larger number are found in regions of late volcanic activity. These include the springs having the higher temperatures, although some springs in areas of late volcanic activity are no hotter than springs in regions where there are no evidences of late volcanic action. In many areas containing deposits formed at moderate and shallow depths hot springs are common. They are found near Creede, Idaho Springs, Dunton, and Ouray, Colo.; Boulder, Mont.; the Comstock lode, Goldfield, and Cornucopia, Nev.; and at many other places. The waters of many of these springs[1] carry considerable concentrations of chlorides and carbonates, with appreciable quantities of sulphates and, in some, borates. Sodium and potassium are the principal positive radicles, though lime and iron are common also. Silica and metallic sulphides are present in some hot-spring waters, and fluorides are not uncommon.

As waters issue at points of least pressure, hot springs are generally found along the apexes of fissures at the lowest places, or along stream beds that they cross. Consequently the material deposited by hot springs is generally mixed with loose rock or other material that accumulates on flood plains or along streams. The materials deposited at the orifices of hot springs in regions of late volcanic activity are generally of simple composition. Limonite, silica, and lime carbonate are most common. Silica occurs as chalcedony and also as crystalline quartz, but generally in crystals that are smaller than those of ore veins. As hot springs generally deposit abundant hydrous iron oxide and silica, many of these deposits resemble gossans that are formed by the weathering of sulphide ores, and it is not surprising that outcrops of sulphide veins have not infrequently been mistaken for hot-spring deposits. Those having abundant lime carbonate,

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[1] Emmons, W. H., and Harrington, G. L.: A Comparison of Waters of Mines and Hot Springs. *Econ. Geol.*, vol. 8, p. 654, 1913.

however, differ greatly, for lime carbonates is seldom stable in sulphide ores under conditions of weathering near the surface. Gold, silver, lead, zinc, antimony, arsenic, mercury, and other metals are found in sinters and tufas, but rarely in workable quantities. Examples of hot-spring deposits that carry metals are numerous; many of them are cited by Clarke.[1]

The hot springs of Wagon Wheel Gap are about 7 miles southeast of Creede, Colo., a camp which has produced much gold, silver, lead, and zinc. The rocks are all effusives of Miocene age.[2] The springs are on the flood plain of Goose Creek, above which mountains rise abruptly 1,000 feet or more. From all the springs bubbles of gas issue continually, and extensive deposits of travertine have been formed on the flood plain, where they have mingled with the wash. Analyses of the waters of the springs are given below.

Fig. 126 is a sketch of the region near the springs and the slope

ANALYSES OF WATERS OF THE HOT SPRINGS OF WAGON WHEEL GAP, COLO.

[Recalculated by G. L. Harrington to parts per million from analyses made at Colorado College in 1904]

	1	2	3
SiO_2	Not det.	84	73
Fe	3	2	1
Al	2	1	Trace
Ca	46	66	17
Mg	53	15	15
Na	347	393	360
K	52	133	156
Li	8	11	9
CO_3	582	353	431
SO_4	161	457	135
Cl	66	195	210
Total	1,320	1,710	1,407
"Carbonic acid and water in bicarbonates."	1,062	788	1,055
Temperature	135°F.	150°F.	140°F.

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[1] CLARKE, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, pp. 179–215, 1916.

[2] EMMONS, W. H., and LARSEN, E. S.: The Hot Springs and the Mineral Deposits of Wagon Wheel Gap, Colorado. *Econ. Geol.*, vol. 8, pp. 235–246, 1913.

of the high ridge which lies east of them. This ridge is strewn with many tons of large barite crystals, and with float of fluorite, jasper, calcite, and opal, sprinkled liberally with pyrite crystals. This material, now oxidized to limonite, carries 0.007 ounce of gold and 0.283 ounce of silver to the ton.

About 100 feet east of spring 1 a lode occupies a zone of sheeted rhyolite 3 feet or more wide. This zone includes veins of barite and fluorite, and pyrite is found along the veins in the country rock, which is highly altered. At 600 feet or more above the level of Goose Creek, in a higher tunnel about 200 feet long, the lode is well exposed. Fluorite and barite are developed in open spaces along the fissure, and pyrite is abundantly present in the walls. Analyses of this material by Edmund Newton, of the Minnesota School of Mines, showed 0.03 ounce of gold and 4.55 ounces of silver to the ton.

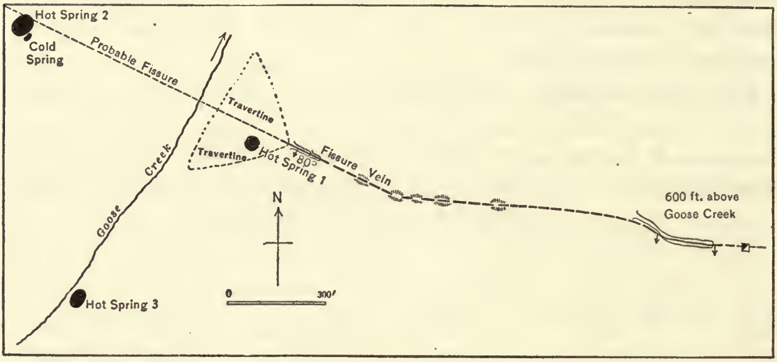

FIG. 126.—Sketch showing position of hot springs and associated mineral deposits of Wagon Wheel Gap, Colorado.

A partial analysis of the travertine made by George Steiger is as follows:

	Per cent.		Per cent.
Pb	None	F	0.220
ZnO	0.007	Cu	None
BaO	0.045		

These veins are exploited for fluorite, which is used by smelters at Pueblo as a flux.

At Ojo Caliente, N. Mex.,[1] about 50 miles north of Santa Fe,

[1] LINDGREN, WALDEMAR: The Hot Springs of Ojo Caliente and Their Deposits. *Econ. Geol.*, vol. 5, pp. 22–27, 1910.

hot springs issue from andesitic tuffs and sands which lie in the valley of a small creek and above which is reddish pre-Cambrian gneiss. About 200 feet above the bed of the gulch a shaft was sunk on a vein 2 or 3 feet wide, filled with rock fragments loosely cemented by fluorite crusts. The vein matter is oxidized, containing limonite and oxide of manganese; the latter is reported to contain silver. About 500 feet southwest of the shaft and directly in the line of the vein, which can be traced in this direction for 200 feet, is a small hill about 75 feet vertically above the shaft. The top of this hill is covered to the extent of about half an acre by a tufaceous hot-spring deposit. A pit 3 feet deep is sunk in a cellular mass composed of calcite, limonite, and 0.4 per cent. of fluorite, with traces of gold and silver.

At Boulder Hot Springs, Mont.,[1] deposits bearing metals are now forming. The country rock is granite (quartz monzonite), a part of the great granite batholith that extends southward beyond Butte. At many places the eroded granite surface shows numerous jasper reefs, formed, according to Weed, along the apexes of fissures through which hot solutions rose. Some of the hot springs issue along such reefs at others the water rises from rocky débris. The hot waters carry soda, lime, and magnesia, as chlorides, sulphates, and carbonates, with a little iron, sulphur, and hydrogen sulphide. Some of the fissures are sheeted zones about 6 feet wide. The granite is highly altered near the fissures, sericite and kaolinite replacing feldspar and quartz. Chalcedony and jasperoid are developed in open spaces, together with calcite, quartz, and stilbite; adularia was identified in a veinlet near the springs. The vein filling carries 0.05 ounce of gold and 0.4 ounce of silver to the ton; the altered granite carries a trace of gold and 0.4 ounce of silver. Some of the altered granite is stained with copper, and some of the red jasperoid shows patches of crystalline hematite. Pyrite is present. According to Weed, the metals and gangue minerals were deposited by solutions such as are now issuing from the fissures.

At Norris Geyser Basin, in Yellowstone National Park,[2] where

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[1] Weed, W. H.: Mineral-vein Formation at Boulder Hot Springs, Mont., U. S. Geol. Survey *Twenty-first Ann. Rept.*, part 2, p. 233, 1900.

[2] Weed, W. H., and Pirsson, L. V.: Occurrence of Sulphur, Orpiment, and Realgar in the Yellowstone National Park. *Am. Jour. Sci.*, 3d ser., vol. 42, pp. 401–405, 1901.

hot springs issue through Tertiary rhyolites, layers of waxy red travertine and realgar, ⅛ inch thick, covered by and alternating with amorphous orpiment, are found in siliceous sinter. Cleavage planes indicating incipient crystallization were identified under the microscope.

Near Anaconda, Mont.,[1] there is a hot-spring deposit of economic value. The area is one of tilted Mesozoic limestone overlain by rhyolite tuffs upon which a travertine cap is deposited. Some of the deposit is eroded, but in places old cones remain. The waters now issuing have a temperature of about 100°F. In channels and trenches they deposit limonite which locally replaces the travertine. The limonite, according to Weed, carries 50 cents to $1.50 in gold to the ton and has been used for flux at the Washoe plant, the gold being recovered by smelting the travertine with copper ores.

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[1] Weed, W. H.: Economic Value of Hot Springs and Hot-spring Deposits. U. S. Geol. Survey *Bull.* 260, p. 601, 1905.

CHAPTER XX

METALLOGENIC PROVINCES AND METALLOGENIC EPOCHS

Metallogenic Provinces.—Petrologists have long used the term "petrographic province" for districts or regions that contain bodies of igneous rocks which, though differing somewhat in composition and character, nevertheless exhibit certain similar features that indicate similar genetic relations. Thus the batholithic intrusive rocks of western Montana are quartz monzonites; those of the Pacific coast are granodiorites; the rocks of the Cripple Creek region in Colorado are phonolites, syenites, etc., characterized by high percentages of alkalies. Similarly the ore deposits in some regions have certain characteristics that suggest nearly related genesis. Thus the zinc and lead deposits of southwestern Wisconsin, of eastern Tennessee, and of southwestern Missouri were all formed in Paleozoic limestone and are all remote from igneous rocks. Mineralogically these deposits are closely similar, and, though differing in structural relations, they may be placed in one group in the interior zinc-lead province. In eastern Ontario near Cobalt there are many small districts that contain silver ores resembling those of Cobalt, which mineralogically are rare and distinctive types. The copper, nickel, and silver deposits of the Lake Superior region in general may be characterized as ores deficient in sulphur or containing less sulphur than the common ores of these metals. The copper ores of Keweenaw Point, Michigan, carry the native metal; the nickel-copper ores of the Sudbury region, in Ontario, contain much pyrrhotite, a sulphide with less sulphur than the commoner iron sulphide pyrite. The silver ores of Cobalt and many districts near by are made up largely of arsenides and native metal. These deposits, though differing greatly as to structural relations and origin, are all in or near basic igneous rocks. The gold belt of California may be considered a metallogenic province, for its deposits are closely similar in composition and character. Because these deposits have been extensively eroded, many of them have furnished the material for enormous placers.

In the Southwest, in Utah, Nevada, Arizona, and New Mexico, deposits of disseminated copper ores have been formed in connection with intrusions of granitic and monzonitic porphyries. These deposits have since been deeply eroded, and conditions have been favorable for much secondary concentration. With respect to both primary and secondary features they constitute a well-defined group.

The geologic processes that operate in any region, such as deformation and denudation, affect the deposits it contains, and these deposits throughout the area in which the processes were operative may be expected to show certain similar features. Thus a great many deposits may be grouped in a relatively small number of provinces, and such a grouping is found to be useful for study and comparison. On the other hand, a relatively small area may contain deposits of totally different character formed at different times or even in the same geologic epoch. The regional grouping is useful, however, if difference of age and origin of deposits are properly recognized.

Metallogenic Epochs.—A metallogenic epoch is a division of geologic time. Ore deposits have been forming since the earliest periods recorded in the rocks, and they are forming today, but they have not formed at an equal rate throughout the geologic ages. Just as they have been concentrated regionally in provinces and subprovinces, so also they have formed more abundantly during one period or another. Iron deposits were formed most abundantly in North America in pre-Cambrian time, especially in the later Huronian epoch, but they formed abundantly also in the Clinton epoch of Silurian time and less abundantly in the Devonian, Carboniferous, and later periods. Gold deposits[1] were formed in the pre-Cambrian, early Cretaceous, early Tertiary, and middle-late Tertiary epochs. Silver deposits also were abundantly formed in pre-Cambrian and especially in Tertiary time. Many copper deposits were formed in the United States in pre-Cambrian, Cretaceous, and early Tertiary time, but only sparingly in the middle and late Tertiary. The age relations of deposits of the principal metals are mentioned in the following chapters, where deposits of the metals are treated separately.

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[1] Lindgren, Waldemar: The Geological Features of the Gold Production of North America. Am. Inst. Min. Eng., *Trans.* vol. 33, pp. 790–845, 1903; Metallogenetic Epochs. *Econ. Geol.*, vol. 4, pp. 409–420, 1909.

CHAPTER XXI

COMPOSITION AND SOURCES OF ASCENDING THERMAL METALLIFEROUS WATERS

Chemical Composition.—Investigation of the composition of the metalliferous deposits and of the nature of hydrothermal alteration along fissures should throw some light on the composition of the metalliferous solutions that have deposited ores. The hot waters circulating in the fissures have deposited, besides the heavy metals, potash, boron, fluorine, carbonates, sulphates, and other compounds. Many regions where igneous rocks have lately been intruded contain hot springs. Nearly all these springs carry alkali chlorides, and many carry carbonates and sulphates. A few carry also boron and fluorine; at some of them hydrogen sulphide and carbon dioxide gas escape. Some of these hot springs issue from fissures where ores are probably being deposited today, and it is a warranted assumption that the waters of the hot springs are closely similar to the residues of solutions such as have deposited metalliferous veins. The average composition of 58 hot springs in regions of volcanic rocks is stated below, where they are compared with mine waters and also with waters of hot springs in areas where there is no evidence of recent volcanism.[1]

Ascending hot waters vary considerably in composition, and the wall-rock alterations they accomplish likewise show great variations. Yet, on reviewing all these alterations and the analyses of the waters of hot springs associated with igneous activity, the conclusion is justified that ascending thermal waters in general are complex solutions, containing varying amounts of sodium, potassium, alkaline earths, and heavy metals dissolved as chlorides, carbonates and sulphides, and subordinately

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[1] Emmons, W. H., and Harrington, G. L.: A Comparison of Waters of Mines and Hot Springs. *Econ. Geol.*, vol. 8, pp. 653–659, 1913.

Analyses of Hot Springs and Mine Waters

	1			2			3			4			5		
	A	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*
Cl	797.07	2.10	39.30	22.97	0.68	0.40	22.480	0.0590	1.11						
Br	0.25	trace	trace	0.01	trace	......	0.003	......	......	22.49	0.059	1.11	41.2	1.1	0.7
I	0.22	trace	....	0.01	trace	......	0.002	......	......						
F	0.12	......	trace	trace	......	......	0.006	......	......						
SO_4	536.35	49.75	7,551.99	15.45	16.15	75.89	11.170	1.0340	157.23	11.17	1.034	157.23	20.4	19.8	97.6
CO_3	628.70	124.04	83.01	18.12	40.27	0.83	20.960	4.1350	2.77	20.96	4.135	2.77	38.4	79.1	1.7
										54.62	5.228	161.11	100.0	100.0	100.0
PO_4	0.03	......	trace	trace	......	trace	0.001	......	......						
AsO_4	0.65	......	trace	0.02	......	trace	0.007	......	......						
B_4O_7	122.83	0.05	trace	3.54	0.02	trace	1.570	0.0006	......						
NO_3	....	0.11	trace	......	0.04	trace	......	0.0018	......	2.50	0.002				
S	14.78	......	0.02	0.43	......	trace	0.920	......	......						
As	0.05	......	....	trace	......	......	......	......	......						
Sb	0.01	......	....	trace	......	......	......	......	......						
Na	1,037.38	6.65	63.28	29.89	2.16	0.64	45.100	0.2890	2.75						
K	49.12	4.97	30.32	1.41	1.61	0.31	1.260	0.1270	0.78						
Li	1.55	trace	....	0.04	trace	......	0.220	......	......	48.15	0.416	3.53	87.4	7.6	3.4
NH_4	28.31	0.02	....	0.82	0.01	......	1.570	......	......						
Ca	71.80	74.08	161.01	2.07	24.05	1.62	3.580	3.6970	8.05						
Sr	0.03	......	....	trace	......	......	......	......	......	5.64	4.744	22.12	10.3	86.6	21.2
Ba	0.03	......	....	trace	......	......	......	......	......						
Mg	25.10	12.74	171.16	0.72	4.14	1.72	2.060	1.0470	14.07						
Mn	0.01	0.08	40.76	trace	0.03	0.41	......	0.0030	1.48						
Fe	3.88	0.26	239.70	0.11	0.08	2.41	0.140	0.0930	[a]10.99						
Al	10.01	2.03	253.97	0.29	0.66	2.55	1.110	0.2250	28.09	1.25	0.321	78.36	2.3	5.8	75.4
Co, Cd, Ni, Pb	....	......	1.22	......	......	0.01	......	......	0.02						
Cu	....	......	1,147.69	......	......	11.53	......	......	36.15						
Zn	....	......	53.14	......	......	0.53	......	......	1.63						
SiO_2	129.07	31.12	53.07	3.72	10.10	0.53	4.280	1.0320	1.76	55.04	5.481	104.01	100.0	100.0	100.0
SiO_3	9.98	......	....	0.29	......	......	0.260	......		4.54	1.032	1.76			
H	3.14	......	61.31	0.09	......	0.62	3.120	......	60.82	3.12	.....	60.82			
	3,470.47	308.00	9,950.93	100.00	100.00	100.00									

[a] 56 per cent. F‴, 44 per cent. Fe″.

A. Average of 58 analyses of hot springs in areas of comparatively late volcanic activity.

B. Average of 17 analyses of hot springs in areas of comparatively remote volcanic activity.

C. Average of 42 analyses of mine waters.

1. Parts per million.
2. Percentage of dissolved material.
3. Results obtained by dividing weight of ion by its valence and parts per million by the quotient.
4. Reacting values of columns, 3, *A*, *B*, *C*, in appropriate chemical groups.
5. Reacting values reduced to percentages of halogens, etc., and of metals.

ANALYSES OF HOT SPRINGS AND MINE WATERS.—(*Continued*)

	Reacting values			Percentages		
	Hot springs (*A*)	Hot springs (*B*)	Mine waters	Hot springs (*A*)	Hot springs (*B*)	Mine waters
Alkalies	48.15	0.416	3.53			
Alkali earths and other metals	6.89	5.065	100.48			
Hydrogen	3.12	....	60.82			
Strong acids	35.24	1.095	158.19			
Weak acids	21.98	4.135	2.77			
Primary salinity	70.48	0.832	7.06	64.0	7.6	2.2
Secondary salinity	....	1.358	200.96	......	12.4	63.5
Tertiary salinity	....	....	108.36	......	......	34.3
Primary alkalinity	25.82	....	....	23.5		
Secondary alkalinity	13.78	8.772	....	12.5	80.0	
	110.08	10.962	316.38	100.0	100.0	100.0
Alkalinity	39.60	8.770				
Acidity	....	....	108.36			

as boron and fluorine compounds and probably sulphates. These substances are present in different proportions in different solutions, and they accomplish different results, even under nearly similar conditions. Probably no two deposits formed by such waters have exactly the same composition, and a single deposit may differ greatly in different parts. Each type, however, grades into other types. Like igneous rocks, they are not set off by sharp divisions, each differentiated from all others. That solutions of compositions suggested by the analyses given above are capable of depositing ores of the various metals is evident from a review of the chemical relations of the metals. A chloride solution will dissolve iron, copper, gold, lead, zinc, and mercury, as well as antimony and arsenic. Silver is soluble in a concentrated alkaline chloride solution. Thus a chloride solution would itself be capable of transporting all these metals.

Carbonate solutions with excess carbon dioxide will dissolve iron, copper, lead, silver, and zinc. Gold is not dissolved in carbonate solutions unless alkaline sulphides or chlorides are present.

A solution of alkali sulphide will dissolve iron, gold, lead, zinc, and mercury. Antimony and arsenic also are very soluble in alkali sulphide solution, and in a concentrated solution copper is dissolved. The presence of antimony and arsenic in an alkali sulphide solution increases the solubility of copper.

Ascending hot waters probably carry abundant gases. Gases bubble up at many hot springs, and in some regions of recent volcanism mine workings are filled with gas. Carbon dioxide is commonly present, and hydrogen sulphide escapes from some springs. These gases tend to keep certain metals in solution. When they escape such metals are thrown down. The escape of gases,[1] together with cooling, decrease of pressure, partial oxidation, dilution, etc., favors the precipitation of metals in the upper regions of the earth's crust. Without doubt the metals are deposited most abundantly within a zone not more than 2 or 3 miles deep, and generally less—in the upper part rather than the lower part of the "zone of fracture" (see page 100). In some deposits carrying bonanzas of gold and silver the maximum deposition appears to have taken place probably not more than 2,000 feet below the surface at the time of deposition.

Sources of Metalliferous Thermal Waters.—Epigenetic ores have been grouped in six classes. They are deposited by aqueous solutions, hot and cold. Pegmatites and contact-metamorphic deposits are formed by solutions, either liquid or gaseous, that

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[1] Tolman, C. F., Jr., and Clark, J. D.: The Oxidation, Solution, and Precipitation of Copper in Electrolytic Solutions and the Dispersion and Precipitation of Copper Sulphides from Colloidal Suspension, with a Geological Discussion. *Econ. Geol.*, vol. 9, pp. 559–592, 1914.

Siebenthal, C. E.: Origin of the Lead and Zinc Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma. U. S. Geol. Survey *Bull.* 606, pp. 33–81, 1915.

have emanated from cooling magmas. Ore bodies formed by cold solutions are deposited mainly by waters of meteoric origin—that is, by rain water that has sunk into the ground. The three classes of vein deposits—those formed in the deep zone, at moderate depths, and at shallow depths—are supposed to have been deposited by hot solutions, because such deposits are essentially confined to areas where igneous rocks are present, and along them the wall rocks show characteristic alterations unlike the changes that are known to result from weathering.[1] Such changes are assumed to have been accomplished by hydrothermal processes (see pages 230–263).

Many deposits of this character have been formed below impervious beds, as if the solutions that deposited them had been halted in their upward journey by those beds. Others extend downward for thousands of feet. They do not show the zonal arrangement that characterizes many ore bodies formed or altered by descending cold solutions. For these and other reasons the solutions that deposited them are supposed to have been ascending.

The sources of such hot ascending solutions have been the subject of much controversy. Three hypotheses may be stated: (1) The deposits of the several vein zones may have been deposited by meteoric waters; (2) they may have been deposited by magmatic waters or by mixtures of meteoric and magmatic waters; or (3) some may have been deposited by meteoric and others by magmatic waters.

The third hypothesis has not met with much favor, probably because the most valuable lode deposits—those of the precious metals, copper, mercury, etc.—exhibit certain features so nearly similar that any hypothesis that is assumed to explain the origin of one must be considered as a possible explanation of the others.

The first hypothesis assumes that the bulk of the ores of the three vein zones have been formed by ascending meteoric waters and that magmatic waters have little or no part in their genesis. This hypothesis, which was accepted by Posepny,[2] was urged by him as opposing the hypothesis of "lateral secretion" ad-

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[1] Steidtmann, Edward: A Graphic Comparison of the Alteration of Rocks by Weathering with Their Alteration by Hot Solutions. *Econ. Geol.*, vol. 3, pp. 381–399, 1908. Stephenson, E. A.: Studies in Hydrothermal Metamorphism. *Jour. Geol.*, vol. 14, pp. 180–199, 1916.

[2] Posepny, Franz: The Genesis of Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 23, pp. 197–369, 1893.

vanced by Sandberger,[1] who maintained that the metals were dissolved from rocks near by—essentially from those that formed the vein walls—and concentrated in the lodes by movement of ground water to the master fissures in which the ore was precipitated. The conception of the deeper meteoric circulation was developed more comprehensively by Van Hise.[2] T. A. Rickard[3] once compared the circulation of water to that which takes place in a house that is heated by hot water. He argued that the solutions sank because they were cold and after becoming heated rose because they were pushed up by colder and therefore heavier columns of water. LeConte[4] also elucidated this theory. Becker[5] had adopted it to explain the genesis of the Comstock lode and of the Pacific coast quicksilver deposits. Becker has discussed the chemistry of the hypothesis at some length. He urged that descending waters, probably carrying sulphates, come into regions of higher temperature, where they meet reducing substances. It has been stated frequently that carbon will reduce sulphates to sulphides. Although this has not been accomplished experimentally at temperatures such as prevail near the surface of the earth, reduction by hydrocarbon compounds is a possible reaction at temperatures well above 100°. Meteoric waters, warmed in depth, might actively dissolve metals and carry them as sulphides, chlorides, and carbonates. In depths where rocks are alkaline the solutions would become alkaline. It is not unlikely that the alkalies would become concentrated under these conditions and that they would dissolve certain metals present in rocks which they traversed. Siebenthal has shown that solutions charged with carbon dioxide under pressure will dissolve metallic sulphides and generate hydrogen sulphide. When the pressure is released, the carbon dioxide and hydrogen sul-

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[1] Sandberger, Fridolin von: Über die Bildung von Erzgängen mittelst Auslaugung des Nebengesteins. *Berg ū. Hüttenm. Zeitung.*, vol. 39, pp. 329–331, 337–339, 390–392, 402–405, 1880.

[2] Van Hise, C. R.: Some Principles Controlling the Deposition of Ores. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 27–177, 1900.

[3] Rickard, T. A.: The Genesis of Ore Deposits; discussion of Posepny's paper. Am. Inst. Min. Eng. *Trans.*, vol. 24, p. 950, 1894.

[4] Le Conte, Joseph: The Genesis of Ore Deposits; discussion of Posepny's paper. Am. Inst. Min. Eng., *Trans.*, vol. 24, pp. 996, 1006, 1894.

[5] Becker, G. F.: Geology of the Comstock Lode and the Washoe District. U. S. Geol. Survey *Mon.* 3, 1882; Geology of the Quicksilver Deposits of the Pacific Slope. U. S. Geol. Survey *Mon.* 13, pp. 449–450, 1881.

phide escape and the metallic sulphides are deposited (see page 479). It is well established also that many igneous[1] and sedimentary[2] rocks contain small amounts of lead, zinc, and some other metals. So far as the chemistry of the process is concerned, there is nothing inherently improbable in the hypothesis that the ascending metalliferous thermal waters are of meteoric origin.

This hypothesis assumes that heat from the intruding magma warms the descending column of cold water and causes it to rise because it is hotter and therefore lighter. The heat that is generated by a great mass of molten magma is doubtless sufficient to stimulate such circulation through a long period if openings are available and favorably spaced. Thus, there is likewise nothing inherently impossible with respect to the physics of the processes on which this hypothesis relies.

In the geologic relations of the deposits this hypothesis finds its most serious difficulties. These are discussed below.

1. Underground observations in deep mines show that the deep-water circulation is much less than it was once supposed to be. Many deep mines are dry.[3] There is a tightening of the ground a few hundred feet below the surface, and the deeper circulation, except in porous sediments and where fracturing is pronounced, is very sluggish (see page 133).

It may be urged that during periods of intrusion the rocks surrounding the intrusive masses are shattered, and that meteoric waters circulate more freely at such periods because openings are more numerous. These openings are formed at an opportune time—when circulation is made active by the stimulus of heat derived from igneous rocks near by. The fact that the deposits at considerable depths are dry when mines are opened, it has

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[1] Emmons, S. F.: Geology and Mining Industry of Leadville, Colo. U. S. Geol. Survey *Mon.* 12, pp. 574–584, 1886.

Robertson, J. D., in Winslow, Arthur: Lead and Zinc Deposits. Mo. Geol. Survey, vol. 7, pp. 479–481, 1894.

[2] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, pp. 627–631, 1916.

[3] Kemp, J. F.: The Rôle of the Igneous Rocks in the Formation of Veins, in Posepny, Franz: "The Genesis of Ore Deposits," pp. 681–809, 1902.

Finch, J. W.: The Circulation of Underground Aqueous Solutions and the Deposition of Lode Ores. Colo. Sci. Soc. *Proc.*, vol. 7, pp. 193–202, 1904.

Rickard, T. A.: Waters, Meteoric and Magmatic. *Min. and Sci. Press,* vol. 96, pp. 872–875, 1908.

been argued, is inconclusive because the openings in the rocks may have been filled by the mineralizing solutions themselves, and the cementation of openings may have rendered the ground surrounding the deposits tight or impervious. However, in many regions little evidence of cementation of openings on a large scale in the country rock near lode deposits can be found.

An example of sluggish circulation is disclosed by developments at Cripple Creek, Colo. The central feature of the district is a mass of volcanic breccia filling the throat of an ancient volcano and inclosed in granite and schists.[1] The breccia is highly porous and soaked with water, whereas the surrounding rocks are practically impervious. Lindgren and Ransome have compared the volcanic complex to a "sponge in a cup." The conditions for circulation outside of the volcanic throat are unfavorable. If the Cripple Creek deposits have been formed through the agency of meteoric waters, these must have been derived from the surrounding granite; they could not have been derived from the very small body of the volcanic plug. If such waters were effective when the ores were formed, they must have descended to great depths[2] near the granite mass and have been driven up by volcanic heat in and near it. But considering the impermeable character of the granite area, this hypothesis, according to Lindgren and Ransome, is untenable.

2. If ascending hot metal-bearing waters are assumed to be meteoric waters that have gathered their load of metals from the rocks they traversed, and if they deposit those metals in and near igneous rocks because they are stimulated to ascend by heat from such rocks, it might be supposed that all intrusive bodies would similarly stimulate the deep circulation. But a great many intrusive rocks are practically barren of ores, as are also the rocks that surround them. This feature of deposition is illustrated in many mining districts. At Tonopah, Nev.,[3] there

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[1] Cross, Whitman, and Penrose, R. A. F., Jr.: Geology and Mining Industries of the Cripple Creek District, Colorado. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 2, pp. 1–209, 1895.

Lindgren, Waldemar, and Ransome, F. L.: Geology and Gold Deposits of the Cripple Creek District, Colorado. U. S. Geol. Survey *Prof. Paper* 54, 1906.

[2] Lindgren, Waldemar, and Ransome, F. L.: *Op. cit.*, p. 227.

[3] Spurr, J. E.: Geology of the Tonopah Mining District. U. S. Geol. Survey *Prof. Paper* 42, 1905.

are many igneous intrusives, but the valuable ore bodies were formed only in connection with one rock unit, the early andesite (later called Mizpah trachyte).[1] At Goldfield, Nev.,[2] there are likewise many intrusive and extrusive igneous bodies, but all the valuable ore bodies are in or near dacite or andesite. At Butte, Mont.,[3] the copper ores are found in the region that has been intruded by quartz porphyry. In several other districts which lie within the great granite mass that contains the Butte deposits but which yield no copper, the major events of geologic history have been broadly similar to those at Butte, except that no quartz porphyry has been intruded. It is inferred, therefore, that there is a genetic connection between the quartz porphyry dikes at Butte and the copper ores and that they may both be derived from the same parent igneous mass.

In these and in many other districts ore deposits are restricted to places in and around certain intrusives to which they are genetically related, and they were deposited in relatively brief geologic epochs, presumably during the cooling of certain magmas that supplied material for the rocks with which they are associated. It is not inferred that the deposits were formed by solutions that emanated from the rocks immediately associated with them. Many of the deposits are veins traversing such rocks; they are commonly referred to a deeper magmatic source—a parent mass perhaps not yet exposed by erosion, a mass that supplied not only the material for dikes and associated igneous rocks but also the solutions that deposited the ores which cut these rocks and are grouped around them.

The igneous history of the Georgetown region, Colorado, is very complicated. There are many dikes of different character, and the ores appear to be genetically related to them, certain types of ores occurring in regions where dikes of certain character predominate.[4] Many additional examples similarly suggest a local relation of certain types of ores to certain types of magmas.

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[1] Spurr, J. E.: Geology and Ore Deposits of Tonopah, Nevada. *Econ. Geol.*, vol. 10, p. 719, 1915.

[2] Ransome, F. L.: Geology and Ore Deposits of Goldfield, Nevada. U. S. Geol. Survey *Prof. Paper* 66, 1909.

[3] Sales, Reno: Ore Deposits at Butte, Montana. Am. Inst. Min. Eng. *Trans.*, vol. 46, pp. 80, 81, 1914.

[4] Spurr J. E., Garrey, G. H., and Ball, S. H.: Economic Geology of the Georgetown Quadrangle, Colorado. U. S. Geol. Survey *Prof. Paper* 63, 1908.

A very common sequence of events[1] in mining districts is intrusion, fissuring and faulting, ore deposition.

3. In some districts several types of ores show a rude zonal arrangement. At Butte there is a central area of copper ores containing chalcocite, enargite, pyrite, and quartz. This area is surrounded by a belt of copper ores with which sphalerite and manganese minerals are practically everywhere associated, and this belt in turn is surrounded by a belt of manganiferous zinc ores, some of which contain much silver.[2] At Tintic, Utah,[3] also, there are belts of mineralization related to a central mass of intrusive monzonite (see page 463), and in some other districts a similar arrangement of types of ores with respect to certain intrusives is indicated. The theory that hot meteoric waters have deposited ores that are so arranged is not satisfactory. It is difficult to harmonize such great differences as must have existed in the waters that deposited the different ores if the waters are assumed to have derived their metal content within areas so small as the mineralized areas above cited, especially as the meteoric solutions must have traversed rocks of essentially the same character during the period when it is assumed that they were gathering the metals from the country rocks. On the other hand, this zonal arrangement might readily be produced by progressive precipitation from a magmatic center.

4. In many districts veins having essentially the same composition are found in rocks of various kinds. At Philipsburg, Mont., silver deposits of similar character are found in veins in granite and crossing shales and limestones. Except in the limestones, where carbonates are more abundant, the veins carry similar ores.[4] If the vein stuff represents material that was dissolved out of the surrounding rocks and deposited in fissures, there should be differences in the vein stuff corresponding to differences in the composition of the surrounding rocks. Thus it appears that in some districts the solutions which are assumed

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[1] SPURR, J. E.: The Relation of Ore Deposition to Faulting. *Econ. Geol.*, vol. 11, pp. 601–622, 1916.

[2] SALES, RENO: *Op. cit.*, p. 58.

[3] LINDGREN, WALDEMAR: Processes of Mineralization and Enrichment in the Tintic Mining District. *Econ. Geol.*, vol. 10, pp. 225–240, 1915.

[4] EMMONS, W. H., and CALKINS, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, p. 187, 1913.

to have traversed rocks of the same character have deposited different ores, and in other districts the solutions which are assumed to have traversed rocks of different character have deposited similar ores. Evidently the composition of the ore-depositing solutions in many districts was substantially independent of the rocks they traversed.

5. The ore deposits in many districts are grouped around intrusive masses of certain composition and character, whereas other intrusive masses near by are barren of ores. In some districts the ores occur around certain parts of igneous masses. Over large areas the relations are so common and so consistent that it is not logical to account for them by mere coincidence.

In Utah[1] ore deposits are widely distributed. The larger intrusive bodies are laccoliths and stocks. Of the stocks some have been deeply eroded or truncated near their bases; others have had merely their apexes or tops removed. The apically truncated stocks are monzonitic or dioritic in composition; the basally truncated stocks are more siliceous, ranging from granodiorite to granite. According to Butler the deposits associated with the laccoliths and basally truncated stocks are commercially unimportant, but those associated with apically truncated stocks have great value. Butler believes that the absence of large deposits associated with laccoliths is to be attributed to the fact that after intrusion the magmas of laccoliths were sealed off from the deep-seated sources. Great ore deposits are rarely associated with small laccoliths, because the amounts of metals in the magmas that form laccoliths are insufficient and differentiation in them is incomplete. In Utah differentiation in stocks, according to Butler, was greater. The mobile constituents of the magmas—particularly water carrying metals in solution—rose toward the surface, while the heavier minerals that were first formed sank to greater depths, rendering the magmas more siliceous. When the mobile constituents arrived at places where the magmas had solidified and fractured, they were guided outward by the fissures and on reaching favorable places the metals they carried were deposited. Butler regards the more deeply truncated stocks as remnants of larger stocks from which the more highly mineralized portions have been eroded.

In the gold-bearing belt of California, as pointed out by Lind-

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[1] Butler, B. S.: Relation of Ore Deposits to Different Types of Intrusive Bodies in Utah. *Econ. Geol.*, vol. 10, pp. 101–122, 1915.

gren,[1] the gold deposits are nearly all located in metamorphic, igneous, and sedimentary rocks around the edges of the great granodiorite batholith which forms the high Sierra and in smaller outlying and doubtless related intrusive bodies of granodiorite (see page 430).

6. Pegmatite veins are products of the crystallization of the more mobile constituents of molten magmas—constituents that are precipitated at lower temperatures than the bulk of the magmatic materials. In some regions pegmatites composed of feldspar and quartz pass by decrease of feldspar into quartz veins. In the Yukon district, Alaska,[2] quartz-feldspar (alaskite) dikes pass gradually into quartz veins by decrease of feldspar. All changes may be noted in a single dike or vein. The quartz veins contain pyrite and calcite, and similar veins near by carry gold. At Silver Peak, Nev.,[3] alaskite and gold quartz veins form two ends of a differentiation series between which rock types showing all gradations are represented. This subject[4] is discussed briefly on page 26.

7. For many reasons, already stated, it is believed that contact-metamorphic deposits are formed by magmatic solutions.[5] In some regions lode deposits grade mineralogically into contact-metamorphic deposits and become more numerous and more typically developed away from the contacts. Such relations are shown in the Coeur d'Alene district, Idaho. There, according to Ransome,[6] the ores of the Granite and Sixteen to One mines, which are in the contact zone encircling one of the largest monzonitic masses, contain garnet, biotite, diopside, and quartz, with magnetite, pyrrhotite, galena, sphalerite, and pyrite, but no siderite. Near the contacts are found veins containing pyr-

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[1] LINDGREN, WALDEMAR: Characteristics of the California Gold-quartz Veins. Geol. Soc. America *Bull.* vol. 6, pp. 221–240, 1896.

[2] SPURR, J. E.: Geology of the Yukon Gold District, Alaska. U. S. Geol. Survey *Eighteenth Ann. Rept.*, part 3, p. 312, 1898.

[3] SPURR, J. E.: Ore Deposits of the Silver Peak Quadrangle, Nevada. U. S. Geol. Survey *Prof. Paper* 55, 1906.

[4] See also SPURR, J. E.: A Consideration of Igneous Rocks and Their Segregation and Differentiation as Related to the Occurrences of Ores. Am. Inst. Min. Eng. *Trans.*, vol. 33, pp. 288–340, 1902.

[5] LINDGREN, WALDEMAR: The Character and Genesis of Certain Contact Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 31, pp. 226–244, 1901.

[6] RANSOME, F. L., and CALKINS, F. C.: The Geology and Ore Deposits of the Coeur d'Alene District, Idaho. U. S. Geol. Survey *Prof. Paper* 62, p. 136, 1908.

rhotite, and magnetite. Away from the contacts the deposits are the typical sideritic galena ores of the Coeur d'Alene district, and these are connected by many gradations with the garnetiferous ores near the contacts.

8. Fluid inclusions are found in many lode ores, especially in those formed in the deeper zone and at moderate depths. Some contain gas bubbles, salt cubes, and a dark solid, probably a metallic substance. Many of the fluid inclusions in pegmatites and in some igneous rocks contain gas bubbles. The distribution and character of the fluid inclusions in rocks and in some ores suggests a genetic relation.

9. As is shown on pages 284–287 there are strong reasons to believe that magmas contain an abundant supply of water—ample at least to account for ore deposition by thermal waters.

Summary.—Certain conclusions seem to be warranted by the facts and conditions reviewed above. Igneous rocks or magmas are the sources of practically all ore deposits, whether they are syngenetic or epigenetic, for all geologic bodies, whether sedimentary, igneous, or metamorphic, are formed of material derived from igneous magmas. Some ore deposits and protores have been formed directly by consolidation of molten magmas. Others have been formed by cold meteoric solutions that have leached the metals from sedimentary or from other rocks. Such deposits have certain marked characteristics (see pages 74 to 83). Other deposits equally characteristic (pages 49 to 73) have been formed by hot ascending solutions. This conclusion is inevitable, for the deposits are almost invariably associated closely with igneous bodies that are exposed. The structural relations of many of the deposits indicate that they have been formed by ascending solutions. There is much evidence that such solutions have been derived from magmatic sources, for in some districts the ores have been deposited only at places where and during periods when volcanic processes were active. Moreover, in many districts the deposits are substantially independent of the rocks they traverse but are grouped with respect to the position of a certain igneous mass or with respect to certain rock types. If the localization of the deposits were due simply to the heat supplied by the igneous bodies and to the stimulation of the meteoric circulation by such heat, the deposits would probably have formed in connection with all intrusives in a region, because the meteoric and structural conditions must have been substantially similar during more than one period of intrusion. During different intrusions meteoric waters undoubtedly mingle with magmatic waters, especially in the ore zones at moderate and shallow depths. It is shown below that magmas contain fluids sufficient to supply the solutions that alter rocks hydro-thermally and deposit ores and to supply contributions to hot springs. It is a rational conclusion that ascending thermal waters are in large measure of magmatic origin. It does not follow that no metalliferous thermal waters are essentially or entirely of meteoric origin.

The Water Content of Molten Magmas.—In considering the sources of ascending thermal waters, the question arises whether molten magmas contain sufficient water to supply the solutions that accomplish hydrothermal alteration, deposit epigenetic ores, and mingling with surface waters issue as hot springs. Direct observations are difficult, yet there are many data bearing on the problem.

1. Practically all igneous rocks contain hydrous minerals. Micas are almost invariably present in deep-seated rocks, and in pegmatites micas and many other hydrous minerals are common. These minerals are primary. They were formed when the molten magma cooled; the water they contain was a part of the magma. Clarke estimates the amount of combined water in the average rock as 1.42 per cent., the average of 959 determinations.[1]

2. Many rocks contain fluid inclusions. These are present in quartz, feldspars, and other minerals but are most common in quartz. In some quartz the inclosed fluids are under pressure and the inclusions are so abundant that the quartz breaks with explosive violence when shattered with a hammer. Not much is known of the composition of the fluid, but probably water, carbon dioxide, and other gases are generally present. The fact that they are now under heavy pressure suggests that they were formed when the magma solidified.

3. Volcanic glasses represent magmas that were chilled so suddenly that there was no opportunity for their crystallization. Some glasses contain high percentages of water, considerably more than the average crystalline rocks. One analysis shows 5.04 per cent.[2] Spherulites and lithophysæ[3] are believed to have

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[1] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 27, 1916.

[2] Clarke, F. W.: *Op. cit.*, p. 435.

[3] Iddings, J. P.: Geology of the Yellowstone National Park. U. S. Geol. Survey *Mon.* 32, part 2, p. 418, 1899.

been localized by the presence of excess of steam or other gases that facilitated incipient crystallization. That great quantities of gases have escaped when lavas were extravasated is shown in nearly every volcanic field. Where pressure on the lavas is relieved, especially at the tops of flows, vesicular and pumiceous phases are developed by escape of the gases in the rapidly cooling and viscous magmas. Some formations are made up of pumice hundreds of feet thick. In the Yellowstone National Park and the adjacent part of Montana, in the San Juan region, Colorado, and in other volcanic regions there are beds of volcanic tuff many hundreds and even thousands of feet thick, extending over areas of hundreds of square miles, made up very largely of minute wind-blown air-laid volcanic dust which has been broken up as it was blown out of volcanic vents. This material is for the most part comminuted lava and pumice mixed with fragments of more compact rock. These formations illustrate the explosive violence of expanding gas on a huge scale.

4. Not only do surface lavas exhale gases, but great volumes of gases rise in areas of recent volcanic activity long after the surface flows have cooled. There is reason to suppose that such gases are, in part at least, if not chiefly, of magmatic origin. At Cripple Creek, Colo.,[1] great quantities of gases enter the mine workings. When the barometer is low they are so abundant as to cause discomfort to the miners and even suffocation. They consist essentially of nitrogen, carbon dioxide, and water, as shown in the analysis below.

VOLUMETRIC ANALYSIS OF GAS FROM THE ELKTON MINE, CRIPPLE CREEK, COLO.

Water vapor	1.4	Hydrogen	0.0
Hydrocarbon vapors	0.0	Methane, etc	0.0
Carbon dioxide	14.7	Nitrogen	76.8
Heavy hydrocarbons	0.0	Argon	1.5
Oxygen	5.6		
Carbon monoxide	0.0		100.0

This gas may be considered a mixture of about 25 per cent. air, 59 per cent. nitrogen, and 14.7 per cent. carbon dioxide, with 1.4 per cent. water vapor.

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[1] LINDGREN, WALDEMAR, and RANSOME, F. L.: Geology and Gold Deposits of Cripple Creek, Colo. U. S. Geol. Survey *Prof. Paper* 54, p. 257, 1906.

On account of their composition and quantity it is believed that these gases were derived from deep-seated cooling igneous rocks. Brun[1] has stated that volcanic rocks recently formed contain much chlorine, but very little water or hydrogen, and that volcanic eruptions are essentially anhydrous. He reports observations made by him at many active volcanoes, among them Kilauea. His conclusions have lost force, however, since Day and Shepherd[2] collected water from the molten lava of Kilauea.

Nearly all rocks, when heated to redness, give off large quantities of gas.[3] This gas is a mixture consisting mainly of hydrogen, carbon dioxide, carbon monoxide, hydrogen sulphide, and marsh gas. The volumes of gas evolved from many rocks are several times the volumes of the rocks themselves. Most of these gases are believed to be formed by heating hydrous and other minerals.[4] Whether the gases are occluded in the rocks or are constituents of hydrous minerals, they indicate the abundant sources of fluids that are capable of dissolving and depositing metals. Calculations by Gautier show that a cubic kilometer of granite would yield 26,400,000 metric tons of water and an amount of hydrogen that on burning would yield 4,266,000 tons.

The volume of the earth is about 260,000,000,000 cubic miles, and its average specific gravity is about 5.57.[5] The volume of the ocean is 302,000,000 cubic miles.[6] Thus the volume of the ocean is approximately 0.12 per cent. of the volume of the solid earth. The weight of water, volume for volume, is about 18 per cent. that of the weight of the average of solid earth matter. The weight of the ocean is thus about 0.02 per cent. that of the earth.

According to Clarke,[7] the average igneous rock contains 1.42 per cent. of combined water (H_2O+) and 0.47 per cent. not com-

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[1] Brun, Albert: "Recherches sur l'exhalaison volcanique," Geneva, 1911.

[2] Day, A. L., and Shepherd, E. S.: Water and Volcanic Activity. Geol. Soc. America *Bull.* vol. 24, pp. 573–606, 1913.

[3] Gautier, Armand: La genèse des eaux thermales et ses rapports avec le volcanisme. *Annales des mines,* 10th ser., vol. 9, pp. 316–390, 1906.

[4] Chamberlin, R. T.: The Gases in Rocks. Carnegie Inst., Washington *Pub.* 106, 1908.

[5] Chamberlin, T. C., and Salisbury, R. D.: "Geology," vol. 1, p. 9, 1905.

[6] Clarke, F. W.: *Op. cit.,* p. 22.

[7] Clarke, F. W.: *Op. cit.,* p. 27. The estimate was obtained by averaging the water content of 645 samples.

bined (H_2O-). If the water contained in the entire rocky part of the earth is estimated as 1.42 per cent. of its mass, it is evident that a loss of only 1.4 per cent. of its water would be sufficient to yield all the water of the ocean. Thus there appears to be an adequate source in the earth itself to supply thermal waters, whether or not the ocean represents, as is thought by some, the long accumulations of magmatic or juvenile waters that have issued at its surface through the geologic ages.

The age of the ocean[1] is estimated as between 50 and 70 million years.[2] If the ocean has been derived from the central rocky sphere through additions of water from hot springs and volcanic vents, such additions would be equivalent to about 5 cubic miles of juvenile or magmatic waters a year.

Origin of Magmas.—Whatever may be accepted as a working hypothesis to account for the thermal waters that have deposited ore veins, the problems relating to the origin of magmas that solidify to form igneous rocks are of vital importance. The fact that many magmas contain small amounts of the metals is established. Many analyses of igneous rocks reveal small amounts of lead, zinc, gold, etc. The ultimate sources of all sedimentary rocks are igneous rocks or solidified magmas. Thus the hot solutions that have deposited ores must have obtained the metals originally in igneous bodies, either directly by magmatic differentiation or less directly by the process of leaching magmatic products. The existence of the ores is itself evidence that they have come from igneous bodies, for igneous bodies are essentially the sources of all other rocks that make up the earth.

Formerly the nebular hypothesis of Kant and Laplace was widely credited. This hypothesis assumes that the solar system was once a ball of gas expanded to the limit of the orbit of the

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[1] Clarke, F. W.: Chemical Denudation. *Smithsonian Misc. Coll.* vol. 56, No. 5, 1910.

Becker, G. F.: Age of the Earth. *Idem*, No. 6, 1910.

[2] This estimate was obtained by dividing the amount of sodium in the ocean by the amount discharged by rivers annually. Several factors, the values of which are more or less uncertain, are applied as corrections for the resulting estimate. The method was first suggested by Halley. The size of the ocean was considered constant. The contributions of sodium in juvenile waters are mentioned by Clarke, but no correction is made for them. An estimate has been made also by calculating the amount of sediments washed to the ocean annually by rivers and estimating the amount of matter in sedimentary rocks. Results obtained by such methods are of course but rude approximations.

outermost planet; as it cooled it threw off rings and these subsequently were gathered, each to become a rotating ball of gas; on cooling they became liquid, and later portions or all became solid. Those who accepted this hypothesis generally regarded the earth as a liquid ball solidified from the surface; volcanism, or igneous injection, was believed to be due to ruptures in the crust which permitted portions of the partly liquid interior to rise to the surface.

The nebular hypothesis, because it encounters insuperable physical and mathematical difficulties, has now been abandoned by many students of earth problems.[1] Chamberlin has proposed an alternate explanation of the earth's origin, the planetesimal hypothesis.[2] This meets the objections to which the nebular hypothesis is open and therefore appears to be more probable. It assumes that the sun and planets were once a system of solid or fluid matter or both, with knots or nebulæ revolving about a central mass, the whole resembling the spiro-nebulæ, which may now be observed in the sky. The central mass became the sun and the knots or nodes became the planets. The larger of the revolving bodies, having greater power of attraction, captured the smaller ones when the latter came within their paths, and thus each of the planetary bodies grew by accretion of other planetesimal matter. The earth is such a planetary body. It may have been made up of solid particles with occluded gases gathered together by infall and capture. It may or may not have been all liquid. Whatever hypothesis appears most probable to the student, it is highly improbable that the interior of the earth is a molten mass. Certainly it is very hot toward the center, yet its great elasticity as shown by the rate and nature of the transmission of earthquake shocks indicates great rigidity. It remains solid because of the great pressures that exist at great depths.

The earth is regarded as an essentially solid body, its heat being due partly to self-compression by its own gravity.[3] The

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[1] Chamberlin, T. C.: An Attempt to Test the Nebular Hypothesis by the Relations of Masses and Momenta. *Jour. Geol.*, vol. 8, pp. 58–73, 1900.

Moulton, E. R.: An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics. *Astrophys. Jour.*, vol. 11, pp. 103–130, 1900.

[2] Chamberlin, T. C., and Salisbury, R. D.: "Geology," vol. 2, Earth History, pp. 38–78, 1905.

[3] Chamberlin, T. C., and Salisbury, R. D.: "Geology," vol. 1, p. 557, 1904.

heat would depend on the intensity of internal pressure. There are reasons to suppose that the flow of heat from the interior to the middle zone would be greater than from the middle zone to the surface, and that the middle zone would for that reason become hotter. Locally materials of that zone would melt, especially those materials which have the lowest melting points. Gases, particularly the "mineralizers" or materials that make for fluidity and lower the melting points of rocks, would aid in solution, and the places where they were abundant would melt first. The molten mass, by fusing or fluxing its way, would rise to the surface, where pressures are lower. As magmas come into regions of lower pressure the temperatures necessary for liquefaction fall, a change which enables the cooling magmas still to remain liquid. Thus, according to Chamberlin and Salisbury, the more fusible material may thread its way upward toward the surface, and when it arrives at the fracture zone it enters any fractures or other openings that are available. Material highly heated and liquid is carried up from the middle zone to the exterior, and this itself tends to keep the earth solid by limiting the size of bodies of molten material accumulated within. The earth is subjected continually to tidal stresses.[1] There is not only an ocean tide, but the solid lithosphere is subjected to tidal movements great enough to be detected and computed. As a result of these stresses the earth is continually kneaded, and the stresses aid in the expulsion of material to the surface, where pressures are lower. The conception may be illustrated by recalling the common practice of freeing gold amalgam from quicksilver in a buckskin sack. More quicksilver is present than unites with the gold to form amalgam. On being gently pressed and kneaded the excess quicksilver is squeezed out of the solid amalgam and presses outward through the pores of the sack.

The genesis of magmas injected within geologic time and of ore deposits related to such magmas would probably be essentially similar, whether the earth was formed as assumed by the nebular hypothesis or as assumed by the planetesimal hypothesis.

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[1] CHAMBERLIN, T. C., and SALISBURY, R. D.: *Op. cit.*, p. 579.

MICHELSON, A. A.: Preliminary Results of Measurements of the Rigidity of the Earth. *Jour. Geol.*, vol. 22, pp. 97–130, 1914.

CHAPTER XXII

IRON

Mineral	Per cent. Fe	Composition
Limonite	59.8	$2Fe_2O_3.3H_2O$
Goethite	62.9	$Fe_2O_3.H_2O$
Turgite	66.3	$2Fe_2O_3.H_2O$
Hematite	70.0	Fe_2O_3
Magnetite	72.3	Fe_3O_4
Siderite	48.3	$FeCO_3$
Melanterite	20.1	$FeSO_4.7H_2O$
Pyrite	46.6	FeS_2
Marcasite	46.6	FeS_2
Pyrrhotite	60.4	Fe_7S_8
Olivine	5.0 to 30.0	$(Mg, Fe)_2SiO_4$
Greenalite	25.0±	Hydrous silicate of iron
Glauconite	25.0±	Hydrous silicate of iron and potash.
Actinolite	15.0±	$Ca(Mg, Fe)_3(SiO_3)_4$
Ilmenite	36.8	$FeTiO_3$
Franklinite	45.0 ±	$(Fe, Mn, Zn) (FeMn)_2O_4$

Ore Minerals of Iron.—Iron is an abundant metal, constituting 4.5 per cent. of the earth's exterior shell.[1] Iron ores are widely distributed and are formed under many geologic conditions. Iron is found in large amounts in many igneous rocks, some of which are rich iron ores. Some sedimentary rocks also are rich enough to mine for iron, and many rocks, sedimentary and igneous, upon weathering yield high-grade iron ores.

Because iron ores are common and because they are easily beneficiated iron is cheap. Iron ores in the United States carry in general 35 to 65 per cent. of iron, and the larger portion of the iron ore now mined carries more than 40 per cent. Where its impurities are easily removed, or where the ore is "self-fluxing," or where silica can be separated from the iron at low cost, ore that carries 30 per cent. of iron or less may be valuable. Iron

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[1] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 34, 1916.

ores sell at $1 to $6 a ton, the price depending on location and composition. Bessemer ores bring higher prices than non-Bessemer ores because they are more cheaply treated. A Bessemer ore is one that will make pig iron with phosphorus content not more than 0.1 per cent.

Of the iron-bearing minerals hematite is by far the most important. At present it supplies over 90 per cent. of the iron ore mined in the United States; limonite, magnetite and siderite supply nearly all the remainder. The other iron minerals are of interest chiefly as protores or material from which workable iron ore may be formed by superficial alteration or weathering. These minerals are nevertheless important because much iron ore has been derived from them through superficial alteration.

Genesis of Iron-ore Deposits.—The ores of iron are in the main syngenetic. Some valuable deposits, including those of the Kiruna district, Sweden, and some of the magnetites of the Adirondacks, New York, have been formed by magmatic segregation. A great many deposits in the United States are sedimentary. These include the Lake Superior hematites, the Clinton iron ores, the black-band carbonate ores, and the Tertiary ores of Texas. The rich hematites of Minas Geraes, Brazil, and the limonite-carbonate ores of Luxemburg, Lorraine, and the Cleveland district, England, and many other regions are also sedimentary beds. Magnetite ores in several districts in Montana, Colorado, California, New Mexico, and Utah are of contact-metamorphic origin (see page 38). Other deposits have been formed in the deep-vein zone.

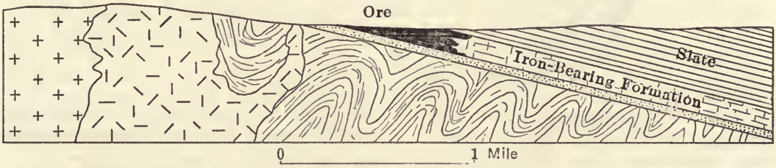

Fig. 127.—Cross-section of iron-ore deposit formed by leaching valueless material from a ferruginous sedimentary protore. (*Ideal section of Mesabi range, Minnesota.*)

Many of the hematite and limonite ores in the United States are weathered products of ferruginous carbonate or ferruginous silicate protores. Some limonite deposits are oxidation products of sulphide deposits—for example, the limonites of Ducktown, Tenn. (pages 164 and 165) and of the Gossan lead, Virginia.

At some places in the West and in Mexico the gossan ores are rich enough in iron to be mined for flux.

All ferruginous materials in the presence of air and water tend to change to the hydrous oxide; a steel rail, an igneous rock, a sulphide ore, or a ferruginous sedimentary rock will all yield limonite. Oxidation or weathering almost invariably results in the concentration of iron near the surface (Figs. 127, 128). The materials other than iron are removed more rapidly than iron, and because of their removal the iron remains in a more concentrated state. Many deposits are valuable only after enrichment by weathering. Thus the Lake Superior iron-bearing formations are all of too low grade to work except where superficial alteration has taken place. Ores of the "lateritic" type like those of Cuba (page 128) have resulted from the thorough decomposition and leaching of iron-rich igneous rocks, other abundant constituents having been removed in part or altogether by long-continued action of air and water (see page 125). Such ores genetically bear a relation to the igneous rocks like that of the gossan to the sulphide ore: in the lateritic deposits the protore is a basic ferruginous igneous rock (Fig. 129); in the gossan the protore is composed of iron sulphides and other minerals (Fig. 130).

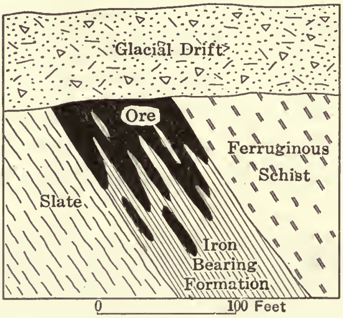

Fig. 128.—Cross-section of iron-ore deposit formed by leaching valueless material from a ferruginous sedimentary protore. (*Ideal section of Cuyuna range, Minnesota.*)

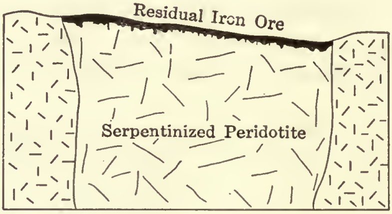

Fig. 129.—Cross-section of iron-ore deposit formed by leaching valueless material from an igneous protore.

Although limonite is in general an end product of weathering of all ferruginous rocks, bodies of nearly pure hematite and magnetite weather much more slowly than the ferruginous carbonates and silicates. Nevertheless hematite and magnetite ores near the surface will generally carry some limonite. On the other hand, limonite may become dehydrated and change to hematite. In a moist climate the more highly hydrated minerals will result from the weathering of the outcrop of a ferruginous material; in a dry climate the less highly hydrated minerals, such as turgite or hematite, will form. Some of the largest and most valuable deposits of iron ore in the world are workable in their original unweathered state. Examples are some magnetites of New York and Pennsylvania, the rich magnetites of the Kiruna district, in Sweden, and the rich sedimentary hematite ores of Minas Geraes, in Brazil.

The Lake Superior ores have been formed mainly by weathering of sedimentary protores; nevertheless they are principally hematite. They have doubtless become dehydrated by exposure under arid conditions, or, in some localities, by removal of water during periods in which they were buried under heavy bodies of later rocks.

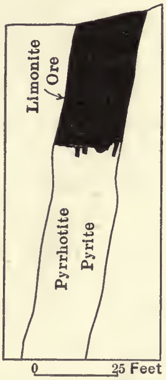

FIG. 130.—Cross-section of iron-ore deposit formed by oxidation and leaching of vein containing iron sulphides.

In migrating slowly under conditions of weathering iron resembles gold and lead, rather than copper and zinc. During weathering, however, some iron is dissolved and precipitated. The cementation of fractures by iron oxide, the replacement of soluble carbonates, and the development of crusts, stalactites, and stalagmites of limonite, etc., attend the weathering of most ferruginous materials.

Under some conditions great quantities of iron are transported in solution[1] and deposited in swamps, in lakes, and in the sea. In the presence of vegetation iron is reduced and tends to remain in the ferrous state. Ferrous salts are more soluble than ferric salts. From these iron may be precipitated by oxidation or by other chemical processes, or through the action of minute organisms known as iron bacteria. Bog and lake iron deposits are commonly produced by the weathering of iron-bearing rocks in moist countries, and locally such deposits are mined for iron. Many of

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[1] HARDER, E. C.: Iron-depositing Bacteria and Their Geologic Relations. U. S. Geol. Survey *Prof. Paper* (in preparation).

them are formed in marshes, swamps, and lakes, and they are abundant in many glaciated regions where drainage has not yet reached adjustment. Small deposits have been laid down within the memory of man. The bog and lake iron ores are not very important commercially, but they are of great interest because they throw light upon the genesis of sedimentary iron ores formed in more remote geologic periods.

In the weathering of rocks containing iron some of the iron is dissolved and carried away in solution, chiefly as ferrous acid carbonate. Some iron may be carried in solution also as sulphate or as salts of various organic acids. While the iron is being carried away in solution there is a tendency for oxidation to take place and for ferric oxide to be deposited by hydrolysis. In dilute solutions some of these iron compounds will form colloids, and much of the iron may be transported in colloidal form to lakes, bogs, or other bodies of water that happen to receive the drainage from an area of weathering ferruginous rocks. Much of the iron, however, remains in solution until it reaches quiet waters.

When iron-bearing solutions reach quiet bodies of water precipitation may take place in various ways, being governed by the form in which the iron exists in the solution and by other constituents that may be present.[1] Most commonly iron is probably carried as bicarbonate in the presence of carbon dioxide. Upon the removal of excess carbon dioxide the iron may be precipitated under reducing conditions as ferrous carbonate or by oxidation and hydrolysis as ferric hydroxide. If decaying organic matter is present in the precipitate ferrous carbonate will remain as such, while any ferric hydroxide present may be reduced and form ferrous carbonate. On the other hand, where oxidizing conditions prevail, ferrous carbonate is readily oxidized to form ferric hydroxide. The precipitation of ferric hydroxide may take place by simple chemical reactions, but in nature, according to Harder, iron bacteria are practically always active in its formation and accumulation at the surface.

Some iron is doubtless carried in solution in the form of ferric salts of organic acids, from which it may be precipitated as ferric hydroxide or as insoluble basic salts of organic acids. These reactions may be those of simple hydrolysis, or it may be that iron bacteria are involved also, as in the precipitation of iron

[1] Harder, E. C.: *Op. cit.*

from ferrous bicarbonate solutions. In the sea reactions with salt water probably favor precipitation under certain conditions. If the solutions react with lime carbonate, iron carbonate or iron oxide may be deposited and lime carbonate be dissolved. The precipitation of ferric oxide from iron sulphate solutions is treated on page 154.

Iron is not dissolved readily under arid conditions. Beds of salt and gypsum are commonly associated with shales and sandstones stained red with hematite.[1] The soluble salts of iron are the ferrous salts rather than the ferric salts. In the absence of organic products that supply reducing agents the iron is likely to be oxidized to the insoluble ferric condition. Thus, in an arid region, the iron may remain as residuary masses, or if it is removed it may be transported mechanically as the ferric oxide rather than in solution as ferrous salt.

Age of Iron-ore Deposits of the United States.—Many sedimentary rocks carry noteworthy percentages of iron. Nearly all limestones, sandstones, and shales are more or less ferruginous. Nodules and layers of iron carbonate, sulphide, or oxide are common in limestone and in shale, and from these rocks iron is frequently concentrated by weathering, forming iron ores. There is evidence that in past geologic time much larger deposits have formed in the sea than are known to be in process of formation today. In several epochs of pre-Cambrian time hundreds of feet of highly ferruginous material were deposited over large areas, and in the Clinton (Silurian) epoch iron was deposited in great quantities over a considerable part of the eastern United States. Much iron was deposited also in the Devonian period, especially in the Oriskany epoch, and iron largely in the form of carbonate was deposited in Carboniferous time. In the Tertiary period extensive iron-bearing rocks were formed in Texas.

Some geologic periods appear to have been more favorable for the production of iron ores than others. It is commonly supposed that the controlling conditions were principally physiographic, and that base-leveled regions that permit long periods of leaching and chemical denudation are more favorable to the development of iron deposits than more rugged regions where

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[1] Tomlinson, C. W.: The Origin of Red Beds. *Jour. Geol.*, vol. 24, pp. 153–179, 238–253, 1916.

the denudation is largely mechanical. It is believed also that certain periods which were marked by the extravasation of igneous rocks were peculiarly favorable to the development of iron ores.[1] Many such rocks carry much iron, and hot waters of magmatic origin, released during volcanic eruptions, are thought by some to have contributed iron to the general run-off.

The deposits now being formed in lakes and seas, so far as is known, do not include iron-bearing formations comparable to those that were laid down in past geologic time. Nodules of iron ore are found by dredging the deep sea, and sediments that are somewhat ferruginous are evidently being deposited today, yet there are no indications that great geologic formations rich in iron are being accumulated. Geologic conditions vary from time to time: one period may be marked by the deposition of phosphate rock; another is more favorable for the formation of coal; still another may be more favorable for the formation of iron ore.

Valuable deposits of iron ore have been formed by magmatic segregation in several geologic periods when igneous agencies were active (see page 9). Those of pre-Cambrian age are noteworthy. Contact-metamorphic deposits of iron ore have been formed in many periods, especially in the Mesozoic and the early part of the Tertiary.

Production.—The iron ores of the United States are of varied genesis, and nearly all the important classes are represented. In 1915 the United States produced over 55 million tons of iron ore, valued at $101,283,984. This ore yielded 30,384,486 tons of pig iron valued at $401,409,604. The greatest item in the production is hematite from the districts of the Lake Superior region. Second in rank are the southern Appalachian districts—Birmingham, Ala., and Chattanooga, Tenn. These regions yield hematite and subordinate amounts of limonite. The Adirondack region, New York, and the districts of southeastern Pennsylvania and northern New Jersey yield magnetite. The most productive iron-producing district in the United States is the Mesabi range in Minnesota.

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[1] Van Hise, C. R., and Leith, C. K.: Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 513, 1911.

Iron Ore Mined in the United States in Gross Tons in 1915[a]

District	Hematite	Brown ore	Magnetite	Carbonate	Total
Marquette (Michigan)	3,817,892				
Menominee (Michigan and Wisconsin)	4,665,465				
Gogebic (Michigan and Wisconsin)	4,996,237				
Vermilion (Minnesota)	1,541,645				
Mesabi (Minnesota)	30,802,409				
Cuyuna (Minnesota)	1,120,606				
Lake Superior total	....	....	....	....	46,944,254
Birmingham	4,213,597	535,332	....	....	4,748,929
Chattanooga	340,481	198,543	....	....	539,024
Adirondack	....	....	699,213	....	699,213
Northern New Jersey and southeastern New York	....	(b)	[b]655,493	....	644,493
Other districts	728,992	754,000	464,130	3,455	1,950,577
	52,227,324	1,488,709	1,807,002	3,455	55,526,490

[a] Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, pp. 285, 295, 1916.

[b] Some brown ore included with magnetite.

LAKE SUPERIOR IRON-ORE DEPOSITS

The iron-ore deposits of the Lake Superior region are the most productive in the United States. They occur in the main, in

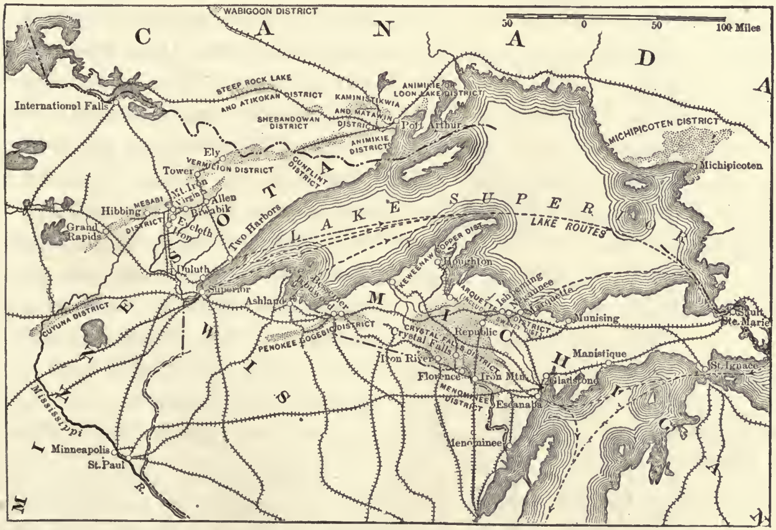

Fig. 131.—Sketch of Lake Superior region showing mining districts and ports. (*After Van Hise and Leith, U. S. Geol. Survey.*)

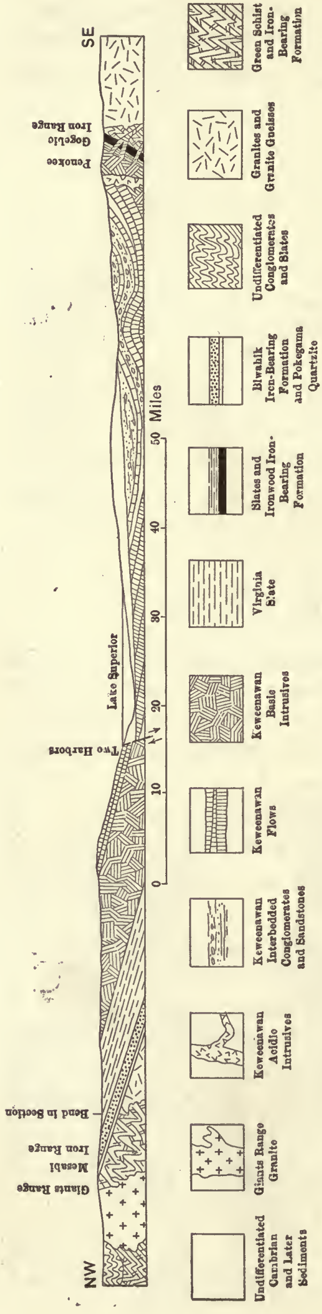

FIG. 132.—Cross-section of Lake Superior region. (*After Van Hise and Leith, U. S. Geol. Survey.*)

long and relatively narrow belts, the so-called iron "ranges." The country is hilly, but the relief is not great; the ranges and peaks rise only a few hundred feet or less above the surrounding country. The ores are carried by rail to upper Lake ports and shipped by boats to lower Lake ports, from which they are distributed to iron furnaces. The positions of the principal districts and their ports are shown in Fig. 131.

Practically all the ores mined in the Lake Superior region are superficially enriched products of pre-Cambrian sedimentary protores. The principal iron-bearing formations are the Soudan (Keewatin), of the Vermilion range; the Negaunee (middle Huronian), of the Marquette range; and the upper Huronian or Animikie formations, of several other ranges. The upper Huronian is the most productive, having yielded over 73 per cent. of the iron ore of the Lake Superior region to the end of 1909.[1]

The principal upper Huronian iron-bearing members in the different districts are named as follows: in the Mesabi range, the Biwabik; in the Penokee-Gogebic, the Ironwood; in the Cuyuna, the Deerwood; in the

[1] VAN HISE, C. R., and LEITH, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 461. 1911.

Menominee, Crystal Falls, Iron River, and Florence districts, the Vulcan. Some ore is mined from the Bijiki schist (upper Huronian) of the Marquette region. The principal ores of that district, however, are in the Negaunee (middle Huronian).

The iron-bearing formations are stratified sedimentary rocks composed chiefly of iron oxide, silica, iron carbonate, and iron silicates. Such rocks are called jasper, ferruginous chert, taconite, greenalite, cherty iron carbonate, etc. By weathering and enrichment they become ore. The process is chiefly solution and removal of silica and carbon dioxide, although locally iron may be dissolved and precipitated as oxide by ground water.

In all the ranges the iron-bearing formations have been tilted, and in some of them closely folded (Fig. 132). The ore-bearing formations have been exposed to weathering through many geologic periods. At some places removal of silica and concentration of iron began in pre-Cambrian time. In the Vermilion range parts of the ore-bearing formation were weathered and metamorphosed to schists in the pre-Cambrian. In the Marquette district the Negaunee formation was altered by weathering before upper Huronian time. All phases of the iron-bearing formation shown in this region, except specular hematite, had developed, for they are represented by pebbles in the upper Huronian. The specular hematite was developed by deep-seated metamorphism of portions of the iron-bearing formation already weathered and enriched. This metamorphism, which gave a secondary cleavage to the iron ore, was accomplished by deformation that took place after the deposition of the upper Huronian sediments.[1] In the Mesabi range concentration by weathering had taken place before the Cretaceous period, for pebbles of weathered ore are found in the conglomerate at the base of the Cretaceous. During long geologic ages large parts of the Lake Superior region have been land; for much of this time the land surface has been relatively low, a condition favoring extensive chemical denudation and deep weathering.

The weathered parts of the ore-bearing formations are found in various positions with respect to the geologic structure. On the Mesabi range the ore deposits are for the most part blankets that lie below the mantle of drift. Here and there the ores extend down the dip of the beds below interstratified lean beds or

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[1] Van Hise, C. R., and Leith, C. K.: *Op. cit.*, p. 278.

CORRELATION OF FORMATIONS OF PRINCIPAL LAKE SUPERIOR IRON-BEARING DISTRICTS. [AFTER VAN HISE AND LEITH]

	Series and group		Marquette district	Menominee district	Penokee-Gogebic district	Mesabi district	Cuyuna district	Vermilion district
Algonkian.	Keweenawan series.	Upper.	Probably represented by intrusives in upper Huronian.	Granite (?)	Absent.	Absent.	Absent.	Absent.
		Middle.			Gabbros, diabases, etc.	Embarrass granite. Diabase. Duluth gabbro.	Basic and acid intrusives and extrusives (Keweenawan?).	Duluth gabbro and diabase sills (Logan sills).
		Lower.			Conglomerates.			
	Huronian series.	Upper Huronian (Animikie group).	Greenstone intrusives and extrusives. Michigamme slate. Partly replaced by volcanic upper-middle Huronian, Clarksburg. Bijiki schist. Goodrich quartzite.	Quinnesec and other schists, greenstone intrusives and extrusives. Michigamme ("Hanbury") slate. Vulcan formation, divided into the Curry, iron-bearing, Brier slate, and Traders, iron-bearing Members.	—Unconformity— Greenstone intrusives and extrusives. Tyler slate. Ironwood formation (iron bearing). Palms formation.	—Unconformity— Acidic and basic intrusive rocks. Virginia slate. Biwabik formation, iron bearing. Pokegama quartzite.	Virginia ("St. Louis") slate, including Deerwood (iron bearing). member.	—Unconformity— Rove slate. Gunflint formation (iron bearing, but non-productive).
		Middle Huronian.	—Unconformity— Negaunee formation (chief productive iron-bearing formation). Siamo slate. Ajibik quartzite.	—Unconformity— Quartzite; in most of district not separated from upper part of Randville dolomite.	Absent.	—Unconformity— Giants Range granite, intrusive. Sediments, equivalent of the Knife Lake slate and Ogishke conglomerate, Vermilion district.	....	—Unconformity— Granites, granite porphyries, dolerites, lamprophyres. Knife Lake slate. Agawa formation (iron bearing, but non-productive). Ogishke conglomerate.
		Lower Huronian.	—Unconformity— Wewe slate Kona dolomite Mesnard quartzite.	—Unconformity— Randville dolomite. Sturgeon quartzite.	—Unconformity— Bad River limestone. Sunday quartzite.			
Archean.	Laurentian series (intrusive into Keewatin).		—Unconformity— Granite, syenite, peridotite. Palmer gneiss.	—Unconformity— Granites and gneisses cut by granite and diabase dikes.	—Unconformity— Granite and granitoid gneiss.	—Unconformity— Granites and porphyries.	....	—Unconformity— Granites and other intrusive rocks.
	Keewatin series.		Kitchi schist and Mona schist.	Green schists.	Greenstones and green schists.	Greenstones, hornblende schists, and porphyries.	....	Soudan formation (iron bearing). Ely greenstone.

below Virginia slate. Some of the deposits are due to leaching along enlarged joints.

In some of the iron ranges the rocks associated with the ores are complexly folded; the ores are in places found in pitching troughs where ground-water circulation has been controlled by impermeable beds or intrusive rocks, or by both. Circulating ground waters conducted along restricted paths through long periods have leached out silica to depths far below the surface. Locally also they have deposited iron oxide, cementing the ore and further enriching it. The concentration of iron oxide by weathering is treated on page 125.

Mesabi Range, Minnesota.—The iron deposits of the Mesabi range[1] are formed by local concentration in a ferruginous sedimentary formation, which extends from a point about 12 miles southwest of Pokegama Lake to Birch Lake, a distance of over 100 miles (Fig. 133). The rocks strike about N. 73°E. and have low dips toward the south. Running parallel to the iron-bearing formation and north of it is a ridge called the Giants Range. In the western part of the district this ridge is only 1,400 feet above sea level and not appreciably higher than the surrounding country. From Virginia eastward it is locally about 400 feet above the country on each side. The lower areas are covered with

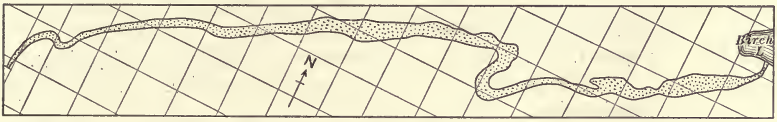

Fig. 133.—Sketch showing trend of Biwabik iron-bearing formation and township lines, Mesabi range, Minnesota.

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[1] Winchell, H. V.: The Mesabi Iron Range. Minn. Geol. and Nat. Hist. Survey *Twentieth Ann. Rept.*, pp. 111–180, 1893.

Winchell, N. H., Grant, U. S., and Spurr, J. E.: Minn. Geol. and Nat. Hist. Survey *Final Report*, vol. 4.

Leith, C. K.: The Mesabi Iron-bearing District of Minnesota. U. S. Geol. Survey *Mon.* 43, 1903.

Spurr, J. E.: The Iron-bearing Rocks of the Mesabi Range in Minnesota. Minn. Geol. and Nat. Hist. Survey *Bull.* 10, pp. 1–268, 1894.

Wolff, J. E.: Recent Geologic Developments on the Mesabi Iron Range, Minnesota. Am. Inst. Min. Eng. *Bull.* 118, pp. 1763–1788, 1916; *Eng. and Min. Jour.*, July 17–Aug. 7, 1914.

Van Barneveld, C. E.: Iron Mining in Minnesota. Minn. Univ. School of Mines Exper. Sta. *Bull.* 1, 1913.

drift. The distribution of the iron-bearing formation has been determined principally by drilling. The following succession of formations is given by Leith.

Quaternary system:	
Pleistocene series	Glacial drift.
Unconformity.	
Cretaceous system.	
Unconformity.	
Algonkian system:	
Keweenawan series	Great basal gabbro (Duluth gabbro) and granite (Embarrass granite), intrusive in all older formations.
Huronian series:	
Unconformity.	
Upper Huronian (Animikie group)	Acidic and basic intrusive rocks. Virginia slate. Biwabik formation (iron-bearing). Pokegama quartzite.
Unconformity.	
Lower-middle Huronian	Giants Range granite, intrusive in lower formation. Slate-graywacke-conglomerate formation.
Unconformity.	
Archean system:	
Laurentian series	Granites and porphyries.
Keewatin series	Greenstone, green schists, and porphyries.

The oldest rocks of the district are Archean greenstones, green schists, and porphyries of the Keewatin series. These are associated with and probably cut by Laurentian granites and porphyries. The Archean rocks are exposed here and there in the central part of the district. Some but not all of the Archean rocks have a well-developed cleavage which is nearly vertical and strikes about parallel to the axis of the range.

The rocks of the Algonkian system rest unconformably upon the Archean rocks and are not so greatly metamorphosed. The oldest member of this system is a sedimentary series of conglomerates, graywackes, and slates, of lower-middle Huronian age. The most extensive exposure is from Eveleth eastward to Biwabik.

The lower-middle Huronian beds strike approximately with the axis of the range and stand nearly vertical. Their thickness is probably between 3,000 and 5,000 feet. These rocks are intruded by the Giants Range granite.

The upper Huronian is composed of (1) the Pokegama quartzite, consisting mainly of quartzite but containing also conglomerate at its base; (2) the Biwabik formation, which rests upon the Pokegama and consists of ferruginous cherts, iron ores, slates, greenalite rocks, and carbonate rocks, with a small amount of coarse detrital material at its base; and (3) the Virginia slate.

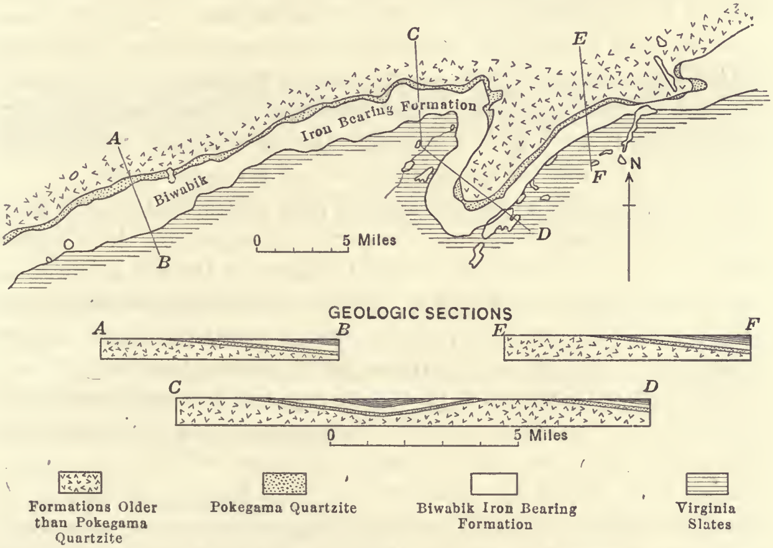

FIG. 134.—Map of central part of Mesabi range, Minnesota, with cross-sections. (*Based on map by C. K. Leith, U. S. Geol. Survey.*)

Between the Pokegama quartzite and the Biwabik formation a slight break in deposition is indicated by conglomerate. Some acidic and basic intrusive igneous rocks are associated with the upper Huronian sediments. All the upper Huronian rocks were formed after the close folding which affected the lower and middle Huronian sedimentary rocks. They are not on edge, but dip at low angles (Fig. 134).

The Pokegama quartzite, the lowest member of the Animikie group, at many places forms the base upon which the iron-bearing formation rests. Its thickness ranges from a few feet to 200 feet, and for so thin a formation it is fairly persistent. From Iron Mountain westward to the end of the iron-bearing district it forms a continuous belt from a few feet to half a mile or more wide. East of Iron Mountain it is nearly continuous to Embarrass Lake.

The Biwabik iron-bearing formation extends along the entire length of the range. Its average thickness is about 620 feet, but owing to the prevailing low dips, the width exposed ranges from a quarter of a mile to 3 miles. The formation is generally covered with glacial drift, which ranges in thickness from 20 to 200 feet. At most places where it is not too thick the drift is removed by stripping, and the ore is loaded into cars with steam shovels. As a rule, the iron-bearing formation rests upon the Pokegama quartzite, but where that is lacking it is in unconformable contact with the older Huronian or the Archean rocks. At the east end of the district the Embarrass granite lies between the iron-bearing formation and the older rocks.

Everywhere along the productive part of the district the iron-bearing formation south of its outcrop is capped by the Virginia slate, but east of Trimble to Birch Lake the Duluth gabbro lies above the iron-bearing rocks. Farther east the formation is cut off by the Duluth gabbro; on the west it probably thins out, the Pokegama quartzite and Virginia slate coming together.

The bulk of the Biwabik formation exposed is ferruginous chert, with which are varying amounts of amphibole, some lime and iron carbonate, and bands and irregular deposits of iron ore. Associated with the slaty layers in the iron-bearing formation or closely adjacent to the overlying Virginia slate are green rocks made up of small granules of a ferrous silicate called greenalite. The greenalite has at some localities been replaced by cherty quartz, magnetite, hematite, limonite, and other minerals, and associated with the greenalite rocks are small quantities of lime and iron carbonates.

At the east end of the range, near Birch Lake, the iron-bearing formation has been metamorphosed by intrusion of gabbro. It is greatly indurated and changed to a rock composed of magnetite, amphibole, olivene and quartz. There are large quantities of this material. Experiments at the School of Mines Experiment Station of the University of Minnesota have shown that it may easily be concentrated to a high-grade Bessemer product in the Davis magnetic concentrator. It is not yet exploited on a commercial scale, but in the future, as iron-ore reserves decrease, it may become an important economic asset.

The Biwabik formation may be subdivided into four members (Figs. 135, 136). These are, from bottom to top, the lower cherty member, the lower slaty member, the upper cherty member, and the upper slaty member. The principal ore bodies are in the cherty members and in the lower slaty member.

Only a small part of the iron-bearing formation is iron ore.

The Virginia slate rests on the Biwabik formation. At the east end of the district, however, the slate is not exposed, and the Biwabik is capped by the Duluth gabbro. Near the contact with the gabbro the mineral composition of the slate is changed and typical heavy silicate minerals are developed. At its base the slate grades into the underlying iron-bearing formation, which is itself slaty in places.

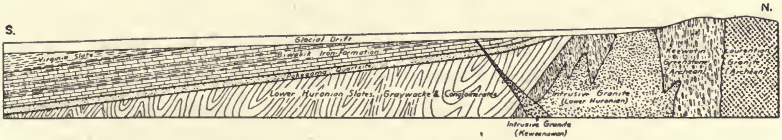

FIG. 135.—Generalized cross-section showing relation of Biwabik iron-bearing formation to associated rocks, in the Mesabi range, Minn. (*After Wolff.*)

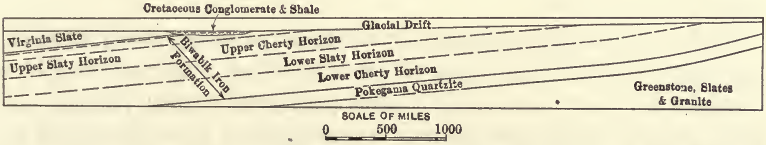

FIG. 136.—Generalized cross-section showing subdivisions of the Biwabik iron-bearing formation, Mesabi range, Minn. (*After Wolff.*)

Flat-lying conglomerates and shales of Cretaceous age, cap the Algonkian and Archean formations here and there. The basal beds of the Cretaceous locally carry detrital iron ores derived from the weathered iron-bearing formation.

The lower-middle Huronian beds and also the Archean formations were subjected to close folding before the upper Huronian sediments, including the Pokegama, the iron-bearing formation, and the Virginia slate, were deposited. Consequently the dips of the older beds are at few places in accord with the dips of the iron-bearing series, which range in general from 5° to 20°, toward the south or southeast. In the vicinity of Virginia, Eveleth, and Gilbert the beds are gently folded and make a broad loop. The dips of the beds are generally normal to the contact of the ore-bearing formation with underlying rocks. West of Virginia the dips are nearly everywhere toward the south, but at Virginia the beds make a sharp swing, and between Virginia and Eveleth the dip is northwestward. About a mile south of Virginia the iron-bearing beds dip west of north at an angle of 10°. At Eveleth the beds make a sharp turn, swinging back again, and in some of the pits northwest of Eveleth the iron-bearing formation dips nearly due west at low angles. East of Eveleth the beds resume their northeast strike, and in the mines between Eveleth and Gilbert they dip nearly southeast. Dips toward the southeast prevail from Gilbert to Biwabik and eastward to the end of the range. This loop and a section across it are shown in Fig. 134.

The iron ores are formed by local concentration in the iron-bearing formation. This formation contains conglomerate and quartzite layers near the base and here and there thin layers of slate or other sedimentary rocks. The ferruginous layers grade laterally into slate bands, and upward the formation grades into the Virginia slate. The formation as a whole is extensive laterally and it has a comparatively uniform thickness like a bed deposited in water.

The iron-bearing formation is not a common type of sedimentary rock. It is thought by some that the waters which deposited the iron protore were derived from volcanic centers and that the iron has been leached out of igneous rocks, possibly by hot waters, and contributed to the sea.[1]

Only small proportions of the Biwabik formation are rich enough to constitute iron ore. These are patches here and there along the eroded surface of the iron-bearing formation. The workable deposits are due to secondary concentration. The ore rarely extends to depths of more than 400 feet below the bed-rock surface, although at some places it is thicker.

The development of the ore from protore has been worked out quantitatively by Van Hise, Leith, and Mead.[2]

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[1] Van Hise, C. R., and Leith, C. K.: Geology of the Lake Superior Region, U. S. Geol. Survey Mon. p. 169, 1911.

[2] Van Hise, C. R., and Leith, C. K.: *Op. cit.*, p. 194.

In the Stevenson mine four samples were taken from a layer in which the ore grades into taconite. No. 1 is fresh or but slightly altered protore; Nos. 2 and 3 are intermediate, partly altered; No. 4 is the leached protore or low-grade iron ore. The chemical analyses and the volume composition are given in the table below:

ANALYSES OF FERRUGINOUS MATERIAL OF THE MESABI RANGE IN VARIOUS STAGES OF ALTERATION

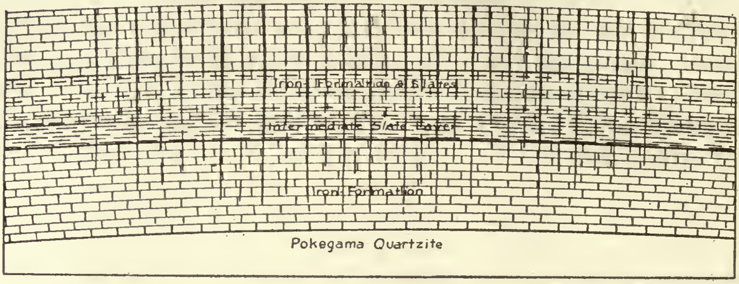
	1	2	3	4
Chemical composition:				
Fe	29.470	33.010	35.260	48.880
SiO_2	52.890	50.080	43.440	25.030
P	0.016	0.016	0.013	0.015
Al_2O_3	0.620	0.350	0.400	0.210
Loss on ignition	2.920	1.650	4.480	3.830
Volume composition:				
Pore space	8.000	16.500	26.300	52.700
Hematite and limonite	32.350	31.250	33.510	30.810
Quartz	57.900	51.400	39.300	16.180
Kaolin	1.740	0.930	0.920	0.340

The original greenalite is altered to taconite (ferruginous chert), which in turn is altered to iron ore by the loss of silica. Through the leaching process magnesia, small amounts of lime, and alkalies are also dissolved out, and these aid in the solution of silica. The net result is to concentrate the iron and to develop corresponding pore space, which, however, is decreased by the slumping of the cellular, porous, weak iron ore. Evidence of such slumping is found in many of the mines, where the ore beds dip toward the thicker and richer parts of the ore body, which in general are near the center.

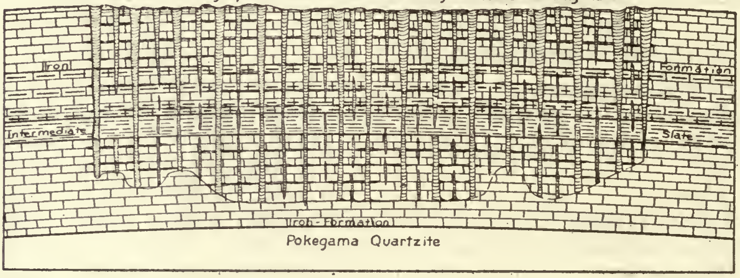
Concentration of this nature in places where water solutions have found more ready access has been going on through long geologic periods. That it was well advanced in Cretaceous time is shown in the detrital ore of the Cretaceous, which carries abundant iron ore in the form of polished pebbles.

Many of the ore bodies have been formed where the iron-bear-

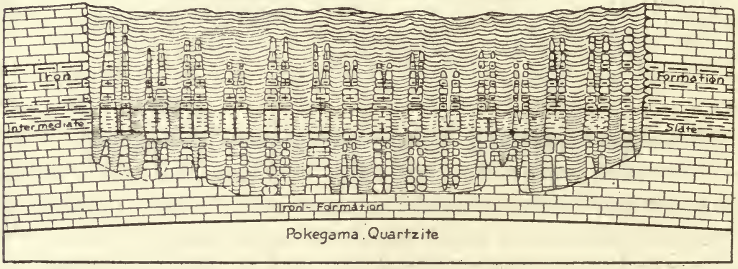
A – Tension Cracks in Iron-Formation on Axis of an Anticline.



B – Ore forming by alteration of Taconite along Fissures & Bedding-Planes.



C – Alteration of Taconite to Ore well advanced.



D – Present Condition of Average Trough Orebody.

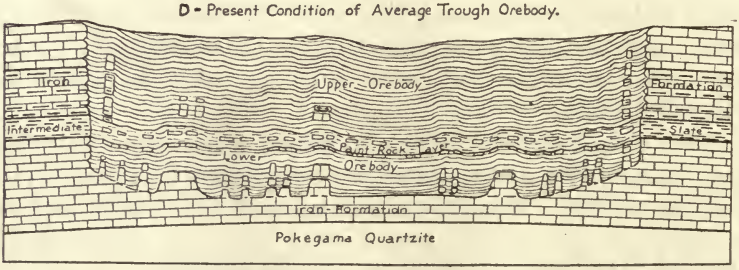


Fig. 137.—Cross-sections showing stages in development of a trough ore body on the axis of a gentle anticline. (*After Wolff.*)

ing formation has been fractured, especially along axes of folds. Where there are only a few closely spaced fractures, a vein-like, vertical mass of ore will be formed. On anticlines the brittle iron-bearing formation is crossed by numerous cracks. Waters circulating along these cracks have developed great ore bodies,[1] in the manner shown diagrammatically by Fig. 137. Section A shows fissures along the crest of a gentle anticline. Section B shows that iron ore has formed along the fractures. The slaty layer near the center of the iron-bearing formation is not readily leached, but leaching may take place in the iron-bearing formation below it, and slumping of the slate develops a trough-like structure in the anticline. Sections C and D show that the slate has altered to "paint rock" which has sagged down owing to shrinkage in the lower ore body.

Cuyuna Range, Minn.—The Cuyuna range,[2] southwest of the Mesabi range, extends from Aitkin through Deerwood and Brainerd to a point beyond Fort Ripley. As now defined it is about 65 miles long in a N. 50° E. direction and ranges in width from 1 or 2 miles to 12 miles. This range is a comparatively late discovery and has recently entered the producing stage. It was discovered by drilling areas showing strong magnetic attraction. The surface is hilly, and the ore-bearing formation is overlain by a thicker mantle of drift than that in the Mesabi range. The geologic succession is as follows:

Quaternary system:	
Pleistocene series	Glacial drift, 15 to 400 feet thick.
Cretaceous system	Sediments, small areas.
Algonkian system:	
Keweenawan (?) series	Igneous rocks, extrusive and intrusive, basic and acidic.

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[1] Wolff, J. E.: Recent Geologic Developments on the Mesabi Iron Range, Minnesota. Am. Inst. Min. Eng. *Bull.* 118, pp. 1763–1787, 1916.

[2] Harder, E. C., and Johnston, A. W.: Preliminary Report on the Geology of East-central Minnesota, Including the Cuyuna Iron-ore District. Minn. Geol. Survey *Bull.* 15, 1917.

Leith, C. K.: The Geology of the Cuyuna Iron Range, Minnesota. *Econ. Geol.*, vol. 2, pp. 145–152, 1907.

Zapffe, Carl: The Cuyuna Iron-ore District of Minnesota. Supplement to the Brainerd (Minn.) *Tribune*, 1910, pp. 32–35 (with map).

Adams, F. S.: The Iron Formation of the Cuyuna Range. *Econ. Geol.*, vol. 5, pp. 729–740, 1910; vol. 6, pp. 60–70, 156–180, 1911.

Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region: U. S. Geol. Survey *Mon.* 52, p. 211, 1911.

Huronian series: Upper Huronian (Animikie group):	Virginia slate: Chloritic, sericitic, quartzose, and carbonaceous slates and schists, with small amounts of interbedded graywackes, quartzite, and limestone. Thickness great. Locally metamorphosed basic igneous rocks are found interlayered with the schists and slates.
	Deerwood iron-bearing member of Virginia slate. Contained originally much iron carbonate but is largely altered to amphibole-magnetite rocks, magnetitic slate, ferruginous chert and slate, and iron ore. It is found in lenses in the Virginia slate, presumably near the base.

The sedimentary rocks strike in general about N. 50° E. and are folded closely, so that they dip at high angles, chiefly to the southeast. East, south and southwest of the district, micaceous, garnetiferous, staurolitic, and hornblendic schists crop out in many places, and are associated with acidic and basic igneous rocks, many of which are intrusive into the schists.

The iron-bearing formation occurs in eight or ten northeastward-trending, discontinuous belts of varying length. The dip of the beds is usually steep, and the prevailing dip is southeast. The formation is inclosed between walls of sericitic, chloritic, or quartzoze schist or slate. Carbonaceous slate also is a common associate. In many places lenses of chloritic schist are interlayered with the iron-bearing beds. The formation consists mainly of ferruginous chert, but ferruginous slate is abundant, and in parts of the district the metamorphosed phases, such as magnetitic slate and amphibole-magnetite rock, are prominent.

The ore bodies are irregularly lens-shaped and lie within the iron-bearing layers; the longer diameter is usually parallel to the bedding of the iron-bearing formation. They may be inclosed within ferruginous chert or slate or other phases of the iron-bearing formation. Many of them are also bounded on one or both sides by schist or slate wall rocks. In places original iron-bearing rocks such as cherty and slaty iron carbonate have been encountered at varying depths below the ore and the associated altered phases of the iron-bearing formation.

The ore bodies have a maximum width of several hundred feet, and some are known to extend along the strike for nearly a mile. The ores are soft and hard and are in the main non-

Bessemer. The principal ore is a much fractured dark-brown hydrated hematite ore containing 50 to 60 per cent. of iron. Locally, however, there are deposits of high-grade dark reddish-purple hematite, much of which is soft, and elsewhere yellowish-brown medium-soft ocherous limonite forms valuable deposits. The ores are in the main superficial alteration products of various types of iron-bearing rocks. Most of them probably do not extend to depths of more than a few hundred feet below the bedrock surface. Many of the iron deposits are highly manganiferous (see page 510).

Penokee-Gogebic Range, Wisconsin and Michigan.—The Penokee-Gogebic range is south of Lake Superior in northern Michigan and Wisconsin. The range trends N. 30° E. and is well defined for a distance of 80 miles. The principal mines are near Hurley, Wis., and near Ironwood, Wakefield, and Bessemer, Mich. (Fig. 138).

The succession of formations in the district is as follows:[1]

Cambrian system	Lake Superior sandstone.
Unconformity.	
Algonkian system:	
Keweenawan series	Gabbros, diabases, conglomerates, etc.
Unconformity.	
Huronian series:	
Upper Huronian (Animikie group)	Greenstone intrusives and extrusives. Tyler slate. Ironwood formation (iron-bearing). Palms formation.
Unconformity.	
Lower Huronian	Bad River limestone. Sunday quartzite.
Unconformity.	
Archean system:	
Laurentian series	Granite and granitoid gneiss.
Eruptive unconformity.	
Keewatin series	Greenstones and green schists.

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[1] Irving, R. D., and Van Hise, C. R.: The Penokee-Gogebic Iron-bearing Series of Michigan and Wisconsin. U. S. Geol. Survey *Mon.* 19, pp. 1–534, 1892.

Chamberlin, T. C.: "Geology of Wisconsin," vol. 1, pp. 3–300, 1883.

Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, pp. 225–250, 1911.

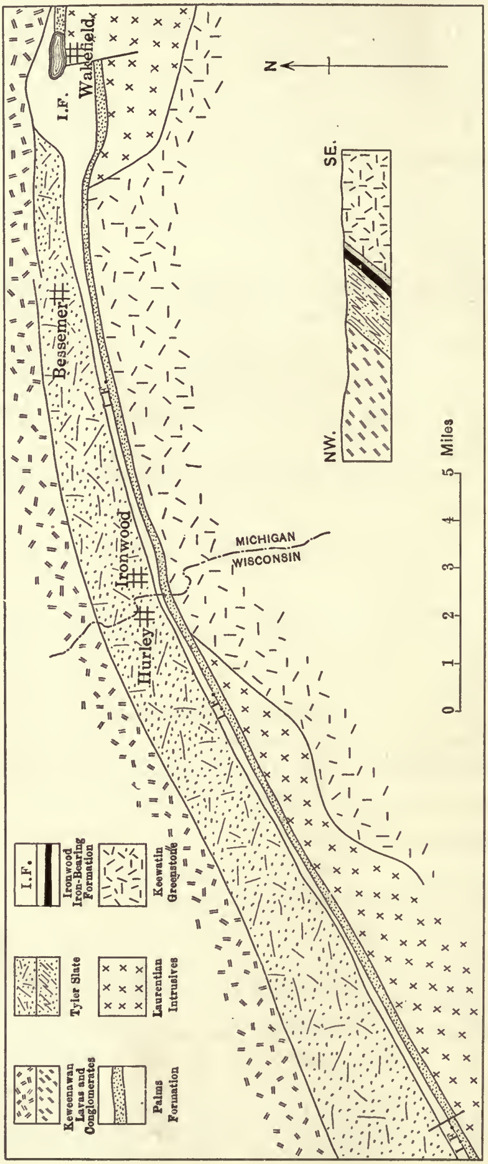

FIG. 138.—Sketch map of part of Penokee-Gogebic district, Wisconsin and Michigan with generalized cross-section. (*Based on map by Irving and Van Hise, U. S. Geol. Survey.*)

In a broad way, the iron-bearing rocks correspond to the Animikie iron-bearing series of the Mesabi range, Minnesota. The Palms formation, the lowest member, is made up of conglomerate, clay slate, and quartzite; the quartzite forms the foot wall of the ore bodies at many places. The Ironwood formation corresponds in age and character to the Biwabik formation of the Mesabi range. It is succeeded by the Tyler slate, corresponding to the Virginia slate on the Mesabi range. On the Mesabi the ore-bearing series dips southeast at low angles; on the Penokee-Gogebic the series dips north or northwest at high angles. Low dips on the Mesabi favor the development of the broad, shallow deposits that are worked by open cuts. Steep dips and narrower outcrops on the Penokee-Gogebic range make it necessary to do the mining mainly underground. In both districts the sedimentary Animikie rocks have a comparatively simple structure, but on the Penokee-Gogebic range they are intruded by many dikes, mainly basic in composition. On the Mesabi range the protore is greenalite rock with some iron carbonate; on the Penokee-Gogebic the protore is chiefly cherty iron carbonate, associated with a little greenalite.

In the Penokee-Gogebic district the Archean rocks include the Keewatin greenstones and schists and the Laurentian granites and gneisses; the Laurentian rocks are intrusive into the Keewatin. The lower Huronian is represented only by the Sunday quartzite and the Bad River limestone, but at most places these formations are not present and the Animikie or upper Huronian rests directly on the Archean. The Laurentian rocks were eroded nearly to base-level before the lower Huronian was deposited; consequently the contact between them is a nearly plane surface.

The upper Huronian comprises the Palms, Ironwood, and Tyler formations, a conformable series which constitutes a northward-dipping monocline. The Palms formation consists of three members: the lowest is a thin conglomerate, above this is a clay slate, and above the slate is a quartzite. The formation is unconformable with the underlying Bad River limestone, although there is no considerable discordance in bedding.

The Ironwood formation is above the Palms and conforms with it in strike and dip. Its outcrop is 1,000 feet wide, or less at most places, but locally, probably where folded or faulted, it is broader. In the eastern part of the district volcanic action prevailed during its deposition, and there the iron beds are thin and impure. The greater part of the formation carries more than 25 per cent. of iron, and considerable portions average 37 per cent. The ore bodies are altered by superficial processes and are much richer in iron. The Ironwood formation consists of slaty, cherty iron carbonate, with some greenalite and ferrodolomite; ferruginous slates and cherts; actinolitic and magnetitic slates, formed largely through metamorphism by Keweenawan intrusive rocks; and black carbonaceous fragmental slates. The iron-bearing carbonates are found usually near the upper part of the formation, where they have been protected from alteration by the Tyler slate. The ferruginous slates and ferruginous cherts are characteristic of the central iron-producing part of the district, and the actinolitic and magnetitic slates are characteristic of the western and eastern parts of the district. The latter also form a belt 20 to 300 feet wide bordering the Keweenawan rocks on the north. Thin black slates are intercalated in the iron-bearing formation. The Ironwood passes gradually into the overlying Tyler slate, which is 7,000 to 11,000 feet thick. It consists of mica schists and slates, graywackes, and clay slates.

Keweenawan basic effusive and intrusive rocks rest on the upper Huronian unconformably, but there is no great discordance in bedding between the Keweenawan flows and the upper Huronian metamorphosed sediments. In the central part of the district the Keweenawan rocks rest on the Tyler slate. At the east and west ends the Keweenawan diagonally crosses the eroded slates and rests on the Ironwood.

The ore bodies are the portions of the Ironwood formation that have been enriched by surface agencies. Only a small area of the iron-bearing formation is workable, and the ores are found only in the central part of the range, in a belt about 26 miles long lying between Potato River, Wisconsin, and a point east of Sunday Lake, Michigan.

Oxidation extends to a depth of more than 2,000 feet. At this depth in the Newport mine the iron-bearing formation is as thoroughly oxidized and leached as it is near the surface. The downward circulation has been controlled by pitching troughs, and thus oxidation has been carried to extraordinary depths in channels where downward-moving waters concentrated. The quartzite of the Palms, which forms the foot wall of the iron-bearing formation, strikes from east to northeast and dips about

65° N. The Tyler slate, above the Ironwood formation, is relatively impervious. The Huronian rocks are cut by many basic (greenstone) dikes of Keweenawan age. These cross the formations, and many of them dip southeast so that they form troughs with the quartzite, the bottoms of the troughs pitching eastward. Some troughs are formed also by westward-pitching dikes intersecting eastward-pitching dikes, and by dikes intersecting slate bands in the ore-bearing formation. These relations are shown by Fig. 139. Several ore bodies may be formed in troughs one below another.

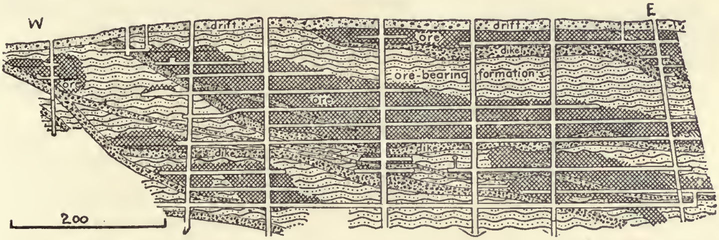

FIG. 139.—Longitudinal section of Ashland mine, Penokee-Gogebic district, Michigan. Shows ore bodies lying on dikes one above the other. (*After Van Hise and Leith, U. S. Geol. Survey from plate furnished by Olcott.*)

Menominee District, Michigan.[1]—The Menominee district is in Michigan not far west of Escanaba, but outlying areas that may properly be included in this district are the Florence area, in Wisconsin, and the Crystal Falls, Iron River, and Metropolitan areas, in Michigan. The rocks in the Menominee district proper are the following:

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[1] BAYLEY, W. S.: The Menominee Ironbearing District of Michigan. U. S. Geol. Survey *Mon.* 46, 1904.

VAN HISE, C. R., and BAYLEY, W. S.: U. S. Geol. Survey *Geol. Atlas*, Menominee Special Folio (No. 62), 1900.

VAN HISE, C. R., and LEITH, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, pp. 329–354, 1911.

HOTCHKISS, W. O.: Mineral-land Classification of Wisconsin. Wis. Geol. and Nat. Hist. Survey *Bull.* 44, 1915.

ALLEN, R. C.: The Iron River Iron-bearing District of Michigan. Mich. Geol. and Biol. Survey *Pub.* 3, Geol. series 2, 1910.

HOTCHKISS, W. O.: "Geology of the Florence District, Wisconsin," 1914.

CLEMENTS, J. M., and SMYTH, H. L.: The Crystal Falls Iron-bearing District of Michigan with a chapter on the Sturgeon River Tongue by W. S. BAYLEY. U. S. Geol. Survey *Mon.* 36, 1899.

Pleistocene series	Glacial deposits.
Cambro-Ordovician	Hermansville limestone.
Cambrian system	Lake Superior sandstone.
Unconformity.	
Algonkian system:	
Keweenawan series	Granite (?).
Huronian series:	
Upper Huronian (Animikie group)	Quinnesec schist and other green schists representing surface eruptions overlying and interbedded with Michigamme slate. Michigamme ("Hanbury") slate, including iron-bearing beds. Vulcan formation, subdivided into Curry iron-bearing member, Brier slate member, and Traders iron-bearing member.
Unconformity.	
Middle Huronian	Quartzite generally not separated from Randville dolomite.
Unconformity.	
Lower Huronian	Randville dolomite. Sturgeon quartzite.
Unconformity.	
Archean system:	
Laurentian series	Granites and gneisses cut by granite and diabase dikes.
Keewatin series	Green schists.

The iron ores are in the Vulcan and Michigamme formations of the Animikie group. The Traders iron-bearing member of the Vulcan consists of conformable beds of ferruginous conglomerates, ferruginous quartzites, heavily ferruginous quartzose slates, and iron-ore deposits. The conglomerates and quartzites are usually at the base of the member, resting upon the Randville dolomite. These rocks contain fragments, usually of quartzite, jaspilite, white quartz, and rocks that make up the Archean complex. In many places the conglomerate contains enough iron to mine. Most of this ore is schistose and carries scales of specularite. The conglomerates and quartzites pass upward into the ferruginous slates. The Brier slate, black and ferruginous, rests conformably above the Traders iron-bearing member. The Curry iron-bearing member consists of interbedded jaspilites and ferruginous quartzose slates and iron-ore deposits. It has resulted from the alteration of greenalite rock like that in the Mesabi district and of iron carbonate like that in the Penokee-

Gogebic district.[1] Greenalite and iron carbonate are not now present, but pseudomorphs of both are abundant.

The Vulcan formation and the overlying Michigamme slate are conformable, and the contact is usually sharp. The Michigamme formation is composed of black and gray clay slates, gray calcareous slates, graphitic slates, graywackes, thin beds of quartzite, local beds of ferruginous dolomite and siderite, and rarer bodies of ferruginous chert and iron oxide.

The formations that carry the ore deposits are all closely folded. The larger deposits rest upon relatively impervious formations whose folds form pitching troughs. Such a trough may be made by the Randville dolomite, underlying the Traders iron-bearing member; by a slate constituting the lower part of the Traders member; or by the Brier slate member, between Traders and Curry iron-bearing members. The dolomite or quartzite formation is likely to furnish an impervious basement, especially where its upper portion has been transformed into a talc schist (Fig. 140).

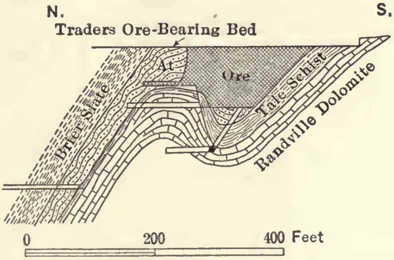

FIG. 140.—Vertical section through Norway-Aragon region, Menominee district, Michigan. Ore is developed in trough. (*After Bayley, U. S. Geol. Survey.*)

Marquette District, Michigan.[2]—The Marquette district extends from Marquette, Mich., on Lake Superior, westward nearly 40 miles, to Lake Michigamme. The principal towns in the district are Marquette, Ishpeming, Negaunee, Champion, and Republic. The outcrops of the Algonkian rocks range in width from about 1 mile to more than 6 miles. From the western part of the main Algonkian area the Republic trough projects southeastward and the Western trough projects southward. The formations are as follows:

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[1] VAN HISE, C. R., and LEITH, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 327, 1911.

[2] VAN HISE, C. R., BAYLEY, W. S., and SMYTH, H. L.: The Marquette Iron-bearing District of Michigan. U. S. Geol. Survey *Mon.* 28, 1897

VAN HISE, C. R., and LEITH, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, pp. 251–283, 1911.

Quaternary system:	
Pleistocene series	Glacial deposits.
Cambrian system:	
Upper Cambrian sandstone (Potsdam sandstone).	
Unconformity.	
Algonkian system:	
Keweenawan series	Not identified but probably represented by part of intrusives in upper Huronian.
Huronian series:	
Upper Huronian (Animikie group).	Greenstone intrusives and extrusives. Michigamme slate (slate and mica schist), locally largely replaced by volcanic Clarksburg formation. Bijiki schist (iron-bearing). Goodrich quartzite (iron-bearing).
Unconformity.	
Middle Huronian	Negaunee formation (chief productive iron-bearing formation). Siamo slate. Ajibik quartzite.
Unconformity.	
Lower Huronian	Wewe slate. Kona dolomite. Mesnard quartzite.
Unconformity.	
Archean system:	
Laurentian series	Granite, syenite, peridotite. Palmer gneiss.
Keewatin series	Kitchi schist and Mona schist, both green schists, the Mona banded and in a few places containing narrow bands of non-productive iron-bearing formation.

Basic igneous dikes and bosses intrude all the Archean and Huronian formations.[1]

The principal iron-bearing formation is the Negaunee (middle Huronian), but the Bijiki schist (upper Huronian) also is iron-bearing. The Goodrich quartzite, which overlies the Negaunee unconformably, includes a basal conglomerate, derived from the underlying Negaunee rocks, that locally contains iron ore. As the Marquette district is structurally a synclinorium, the Negaunee formation is complexly folded so that it crops out over a large area, especially in the east end of the district (Fig. 141).

The protore in the Negaunee formation was originally iron carbonate and greenalite interbedded with more or less slate and

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[1] Van Hise, C. R., Bayley, W. S., and Smyth, H. L.: *Op. cit.*

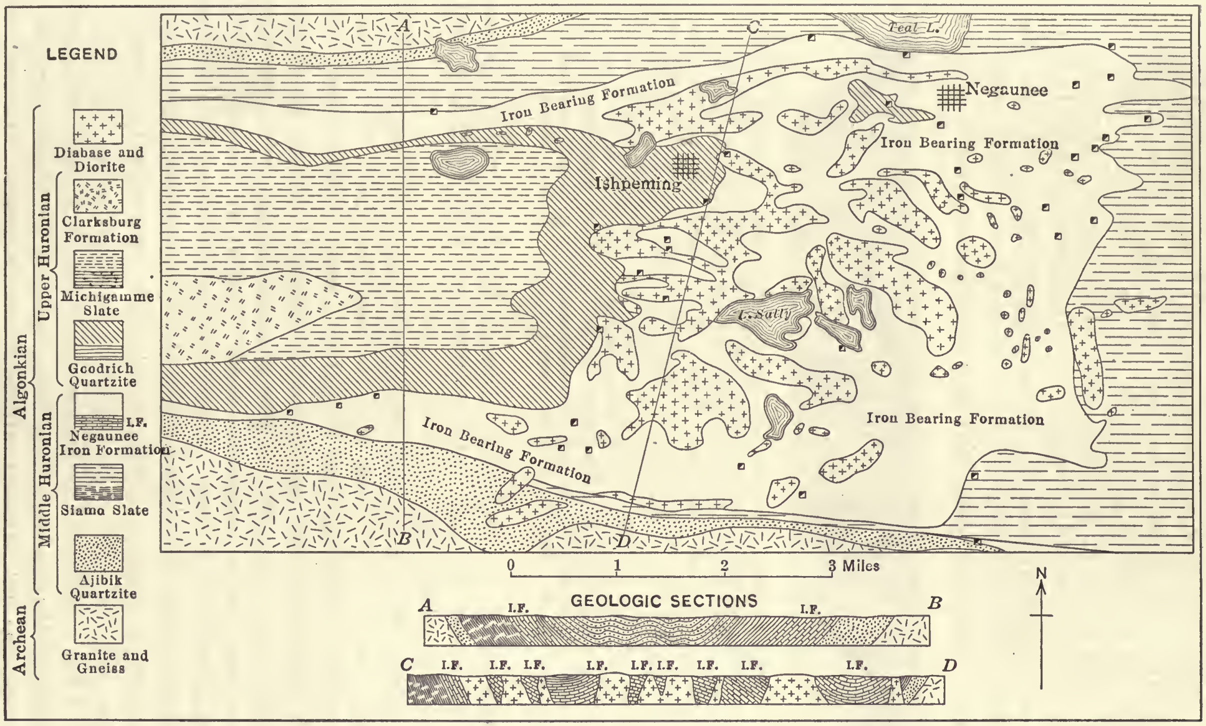

FIG. 141.—Map of part of Marquette district, Michigan. The map shows part of a synclinorium with axes pitching west exposing a broad area of iron-bearing formation. (*Based on map by Van Hise and Bayley, U. S. Geol. Survey.*)

containing much detrital ferric oxide at the base of the formation. The alteration was accomplished by oxidation and hydration of the iron minerals in place, leaching of silica, and introduction of secondary iron oxide and iron carbonate dissolved from other parts of the formation. The flow of water concentrating the ore moved principally in planes parallel to the bedding and was especially effective in pitching troughs. The pitching troughs in this district are formed where a basic dike or boss cuts an impervious bed, where two igneous bodies are joined, or where an impervious bed is folded. Ores of the Negaunee formation are found near the base, in the middle zone of the formation, and near the top (Fig. 142).

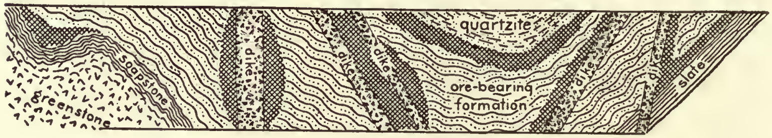

Fig. 142.—Generalized section in Marquette district, Michigan, showing relations of all classes of ore deposits to associated formations. On the right is soft ore resting in a V-shaped trough between the Siamo slate and a dike of soapstone. In the lower central part of the figure the more common relations of soft ore to vertical and inclined dikes cutting the jasper are shown. The ore may rest upon an inclined dike, between two inclined dikes, and upon the upper of the two, or be on both sides of a nearly vertical dike. In the upper central part of the figure are seen the relations of the hard ore to the Negaunee formation and the Goodrich quartzite. At the left is soft ore resting in a trough of soapstone which grades downward into greenstone. (*After Van Hise, Bayley and Smyth, U. S. Geol. Survey.*)

The ores of the lower and middle portions of the Negaunee are mainly soft, but the ores near the top are hard. The middle Huronian, including the Negaunee, was raised above sea level, weathered, and partly eroded before the upper Huronian sediments were deposited. The weathered Negaunee rocks near the ancient surface were doubtless enriched by the removal of material other than iron. After subsidence and deposition of the overlying upper Huronian, the rocks were metamorphosed and deformed by pressure. The enriched ores were thereby changed to specular hematite of high grade. In the iron-bearing formation of the middle and lower horizons of the Negaunee, silica and alkaline earths had not then been removed by weathering, and the rock was not oxidized during the early stage. The concentration of the iron at these horizons was brought about by surface waters at a later period, after the ores in the upper part of the formation had been rendered hard and schistose by dynamic agencies.

The Vermilion Range, Minnesota.—The Vermilion Range,[1] in northeastern Minnesota, extends from a point near the west end of Vermilion Lake about 20° north of east to Gunflint Lake, on the Canadian boundary. It is about 100 miles long and from 5 to 15 miles wide.

The stratigraphic succession, as stated by Clements, is as follows:

Quaternary system:	
Pleistocene series	Glacial drift.
Unconformity.	
Algonkian system:	
Keweenawan series	Duluth gabbro and Logan sills.
Unconformity.	
Huronian series:	
Upper Huronian (Animikie group).	Rove slate. Gunflint formation (iron-bearing).
Unconformity.	
Lower-middle Huronian	Intrusive rocks: Granites, granite porphyries, dolerites. Knife Lake slate. Agawa formation (iron-bearing). Ogishke conglomerate.
Unconformity.	
Archean system:	
Laurentian series	Granite of Basswood Lake and other intrusive rocks.
Keewatin series	Soudan formation (iron-bearing). Ely greenstone, a basic igneous and largely volcanic rock.

The Ely greenstone is the oldest and the most extensive formation in this district. It consists mainly of altered, basic igneous rocks, probably in the main surface flows. At many places these rocks are highly schistose. The Soudan formation, which was deposited above the Ely greenstone, is the oldest iron-bearing formation in the district. It is made up chiefly of beds of jasper and contains also some slates and conglomerates. Some beds

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[1] Winchell, N. H., Grant, U. S., and Winchell, H. V.: Minn. Geol. and Nat. Hist. Survey *Final Rept.*, vol. 4, 1898.

Clements, J. M.: The Vermilion Iron-bearing District of Minnesota. U. S. Geol. Survey *Mon.* 45, p. 463, 1903.

Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, pp. 118–143, 1911.

are composed largely of iron oxides or iron carbonates. The Ely greenstone and the Soudan formation are intruded by granite, felsite, and porphyries, which locally are metamorphosed to schists. These and the rocks they intrude were deformed and otherwise altered and in places were eroded before the sediments of the next system, the Algonkian, were deposited.

The lowest of the Algonkian rocks are of lower-middle Huronian age. The oldest member of this series is the Ogishke conglomerate, which locally has a thickness of over 1,000 feet. At some places, however, it is lacking. Above the Ogishke, in the eastern part of the district, is the Agawa formation, which contains beds of slate, jasper, iron oxides, and iron carbonates. This formation reaches a thickness of 50 feet and contains some unimportant iron ores.

Above the Agawa is the Knife Lake slate, probably several thousand feet thick. The Knife Lake slate and older formations are intruded by the Giants Range, Snowbank, and Cacaquabic granites.

The upper Huronian rocks that contain the iron ores in the Mesabi range are of little value in the Vermilion district, although they occur in a small area west of Gunflint Lake.

The iron ores of the Vermilion range are almost exclusively in the Soudan formation and in places are 2,000 feet below the surface. The principal developments are at Ely and Tower. After the iron-bearing formation was subjected to close folding, erosion removed the upper parts of many folds. Consequently the remnants of the formation are found at many places in pitching troughs, which as a rule are bottomed by the Ely greenstone or by the soapstone or paint-rock—in general the altered phases of the Ely greenstone—or of certain aluminous or magnesian portions of the Soudan formation. The paint-rock or soapstone and associated rocks are comparatively impervious to water. The Soudan formation consisted originally of cherty iron carbonate and probably some banded chert and iron oxide. Surface waters circulating down the tilted troughs leached out the silica, leaving the iron oxide concentrated. Some of this concentration took place before the lower Huronian sediments were deposited, as is indicated by the fact that the lower Huronian conglomerates contain detrital iron ores. Close folding after the lower Huronian deposition rendered the ores hard, anhydrous, and crystalline. At Ely much concentration has taken place also since the deposition of the lower Huronian. Because the ore formations in the Vermilion district were closely folded after some concentration by ground water had taken place, the enriched ores are locally deep-lying.

CLINTON HEMATITE DEPOSITS

Hematite deposits are found at many places along the outcrops of the Clinton (Silurian) formation from New York to Alabama but are workable only here and there. Valuable deposits of the Clinton type have been found in New York, Pennsylvania, Virginia, Tennessee, Georgia, Alabama and Wisconsin.

The deposits are lenses in sandstone and shale and occur at several horizons in the formation. At some places there are three or four beds, generally less than 10 feet thick, although some are much thicker. At Birmingham, Ala., the "Big seam" is 16 to 40 feet thick. Two types of ore are noteworthy—the fossil ore, made up of fossil fragments, mainly those of lime-secreting organisms replaced by iron oxide, and oolitic ore, made up of small spherules. Some of the ore is soft and some is hard. The soft ores are the weathered parts of the seams; they form the outcrops and extend downward for varying distances. Below them the hard ore is found. The soft ore carries about 50 per cent. of iron and 12 per cent. of silica. The hard ore is of lower grade and carries more lime. Its composition is approximately as follows: Iron 35 per cent., silica 25 per cent., lime 20 per cent. By mixing hard and soft ores a self-fluxing furnace charge is obtained; thus the ores are cheaply beneficiated.

The reserves of the Clinton ores are large. In the Birmingham region 358,470,000 tons was estimated as available in 1909.[1] In the region tributary to Chattanooga, Tenn., nearly 100,000,000 tons was estimated as available; in New York about 30,000,000 tons; and in Dodge County, Wisconsin, about the same tonnage as in New York. The structural conditions in these regions indicate that these estimates are low.

Birmingham Region, Alabama.—In the Birmingham district, Alabama,[2] the sedimentary rocks, including the Clinton beds, are

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[1] Hayes, C. W.: Iron Ores in the United States. U. S. Geol. Survey *Bull.* 394, p. 90, 1909.

[2] Burchard, E. F., Butts, Charles, and Eckel, E. C.: Iron Ores, Fuels, and Fluxes of the Birmingham District, Alabama. U. S. Geol. Survey *Bull.* 400, 1910.

folded and faulted, and the Clinton ores crop out as long, narrow strips striking northeast (Fig. 143). The section includes beds ranging from the Cambrian to Carboniferous, and because these beds are folded and eroded, their products, iron ore, coal, and limestone flux, are brought near together. The region, to use an engineering phrase, may be termed "self-contained," for all the materials necessary for the manufacture of steel are abundantly present within a radius of a few miles. The ores, though of lower grade than the Lake Superior hematites, can compete with them, because good coke is made in their vicinity and because they command the Southern market for steel. They carry considerable phosphorus and are non-Bessemer. The development of the open-hearth process of steel making has greatly enhanced their value.

A generalized section of the rocks of the Birmingham district is shown below.

		Feet
Tertiary: ?Lafayette formation. Cretaceous: Tuscaloosa formation.	Present in extreme southwestern part of district.	
Carboniferous:		
Pennsylvanian: Pottsville formation ("Coal Measures")		2,600 to 7,000
Unconformity.		
Mississippian:		
Parkwood formation		0 to 2,000
Pennington shale (30–300 feet). Bangor limestone (670 feet); includes Hartselle sandstone member (100 + feet).	Floyd shale	1,000 ±
Fort Payne chert		200 to 250
Unconformity.		
Devonian:		
Chattanooga shale. Frog Mountain sandstone.		1 to 25
Unconformity.		
Silurian: Clinton (Rockwood) formation		250 to 500
Unconformity.		
Ordovician: Chickamauga (Pelham) limestone		200 to 1,000
Unconformity.		
Cambro-Ordovician: Knox dolomite (includes at base Ketona dolomite member, 600 feet)		3,300
Cambrian:		
Conasauga (Coosa) limestone		1,000 +
Rome (Montevallo) formation (great thickness).		
		7,351 to 16,075

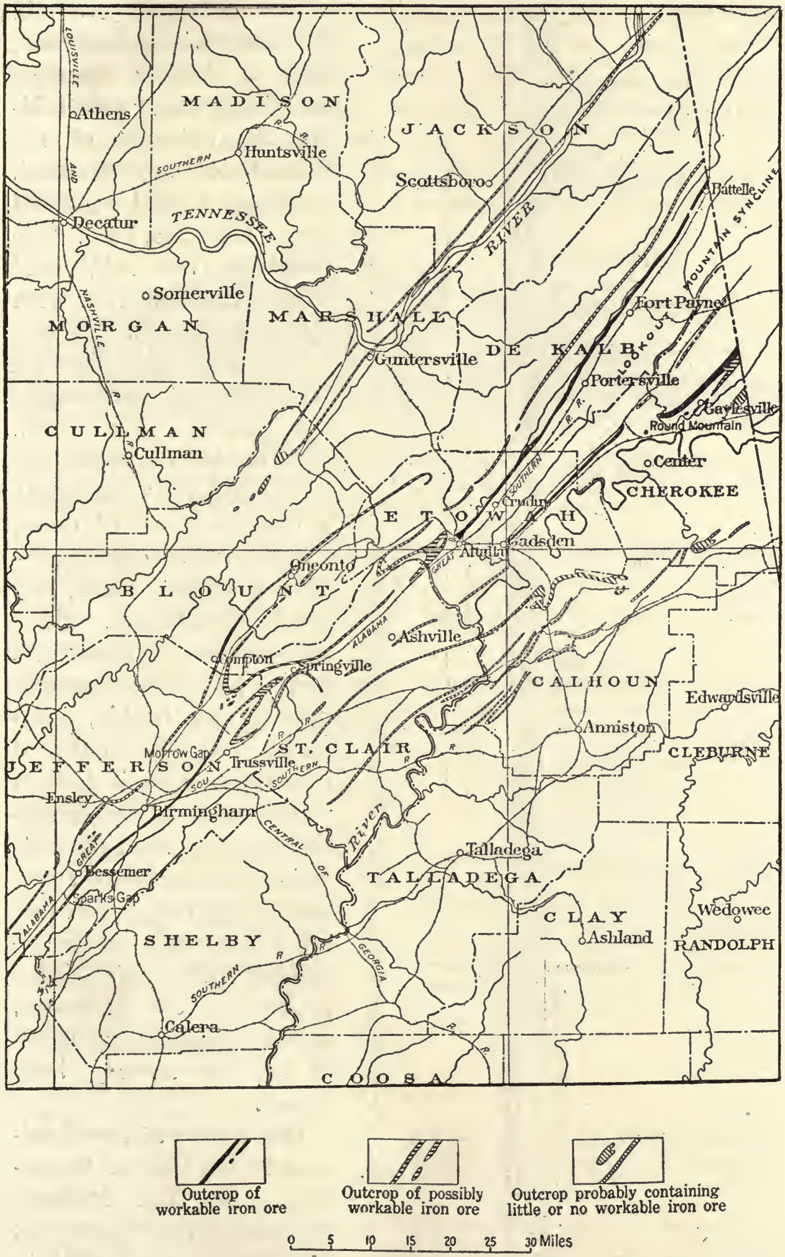

FIG. 143.—Map of region near Birmingham, Alabama. (*After Burchard, U. S. Geol. Survey.*)

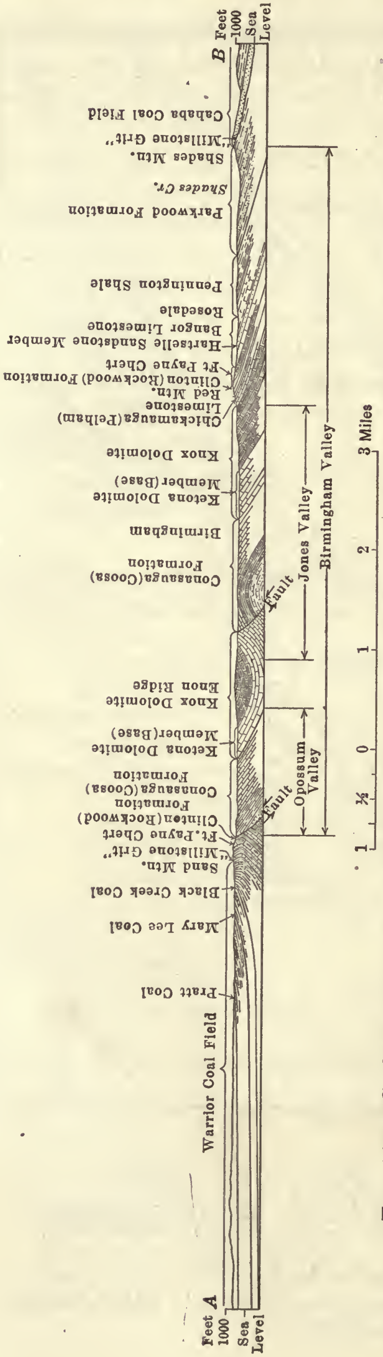

FIG. 144.—Geologic section across valley at Birmingham, Alabama. (*After Burchard, U. S. Geol. Survey.*)

The principal fold in the district is an anticline, with a shallow syncline near its center: by the folding the outcrops of the Clinton ore are repeated, forming several parallel belts (Figs. 143, 144). The trend of the folds and therefore of the rock beds also is northeast.

The ore bodies dip with the rocks at moderately low angles (Fig. 145). Where the ore beds are weathered, lime carbonate is dissolved out of them, thereby increasing the proportion of iron, silica, and other constituents. Such altered ore is termed "soft ore," for it is usually porous and friable, compared with the unaltered material, which is termed "hard ore." The alteration extends from the outcrop for distances of a few feet to 400 feet. The soft ore is generally more accessible and of higher grade than the hard ore, and in consequence much of it has already been mined.

Ore occurs at four horizons in the Clinton formation. (1) The Hickory Nut seam, the highest one, is of too poor a grade to work under present conditions. It is a sandy, ferruginous bed and is named from the presence of a fossil brachiopod which looks like a hickory nut in a partly opened hull. (2) The Ida seam is of low grade but workable locally. It is 2 to 6 feet thick and is siliceous and associated with sandstones. (3) The Big seam, 20 to 50 feet below the Ida and from 16 to 30 feet thick, is persistent along the strike and of good grade, although rarely more than 10 or 12 feet of it is worked. (4) The Irondale seam, the lowest one, is thin but locally of excellent grade. A typical section of the Clinton showing the Big and Irondale seams is given below.

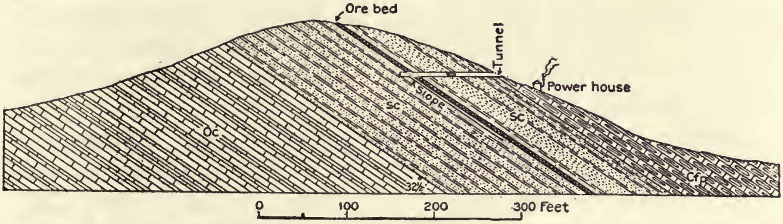

FIG. 145.—Section showing Clinton ore in Birmingham region, Alabama. *Sc*, Clinton (Rockwood) formation; *Oc*, Chickamauga limestone; *Cfp*, Fort Payne chert. (*After Burchard, U. S. Geol. Survey.*)

CHARACTER OF BIG AND IRONDALE SEAMS 1 MILE NORTHEAST OF RED GAP, NEAR IRONDALE, ALA.

Strata	Thickness	Character
Sandstone.		
Big seam:	*Ft. in.*	
Ore, sandy	1 8	Unweathered ore: Metallic iron, 16–20 per cent.; insoluble, 40± per cent.; lime, 18± per cent.
Ore, lean, with fine quartz pebbles.	5	
Ore, massive, cross-bedded, mined.	7	Hard ore, averages metallic iron, 36 per cent.; insoluble, 26 per cent.; lime, 20 per cent.
Ore, similar in appearance to above, but not mined at present.	6	Percentage of iron grades down from 35 at top to less than 20 at bottom; insoluble rises to more than 60 per cent.
Sandstone, ferruginous, lean ore, and shale, in thin strata.	20	
Shale	0 to 6	
Sandstone, very hard	3	
"Gouge," calcareous	6	
Irondale seam: Ore, mined	5	Semihard ore, averages metallic iron, 37 per cent.; insoluble, 29 per cent.; lime carbonate, 14.25 per cent.
Shale, hard.		

The ores are sedimentary. Below the zone of surface leaching they extend thousands of feet without material change.

The occurrence of fragments of the ore in overlying beds of limestone in the Clinton formation, as described by Smyth[1] points to the fact that the ore had been formed prior to the deposition of this limestone.

Smyth, Burchard, and Eckel agree that the ores are of marine origin. There is reason to suppose that the iron replaced the lime carbonate before the beds were deeply buried, possibly before they were consolidated, or even while they were exposed to sea water. Sea water carries iron, and iron replaces lime carbonate, as the iron salts, either carbonate or oxide, are less soluble than those of lime.

Eastern Tennessee Iron Deposits.—In eastern Tennessee, extending from Chattanooga northeastward across the State to Middleboro, Ky., and beyond, a distance of about 150 miles, Silurian beds crop out almost continuously. In this belt, which is practically in the strike of the Clinton beds of Birmingham, Ala., and also in some outlying areas, there are valuable bodies of iron ore in the "Rockwood" formation, which corresponds to the Clinton in Alabama and New York.

The rocks of this area (Fig. 146) are of sedimentary origin and range from the Cambrian to the Carboniferous. They are folded, generally in open anticlines and synclines, and are faulted along reverse or thrust faults that generally dip at low angles. Locally, however, the folding is close, and overturned anticlines are developed.[2]

The "Rockwood" ore crops out along the foot of the Cumberland escarpment from a point near Chattanooga to the northern border of the State at Cumberland Gap and in several separate areas in the Tennessee Valley. There are strips of outcrop that extend continuously 15 to 20 miles. The normal dip of the rocks along the escarpment is northwest, but in many places where closely folded the ore beds dip to the southeast, or away from the mountain.

As in the Birmingham district, the ore occurs in lenticular sedimentary beds. It is mainly of two types, fossil ore and granular ore. The fossil ore consists of aggregates of fossils, including bryozoans, crinoids, corals, brachiopods, and trilo-

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[1] Smyth, C. H., Jr., in Bain, H. F., and others: "Types of Ore Deposits," pp. 33–52, 1911. See also Am. Jour. Sci., 3d ser., vol. 43, pp. 487–496, 1892.

[2] Burchard, E. F.: The Red Iron Ores of East Tennessee. Tenn. Geol. Survey *Bull.* 16, p. 27, 1913.

bites. These fossils were originally calcium carbonate. There are calcareous streaks in the ore in which many of the fossil fragments are still composed mainly of calcite, but in other places the fossil forms are composed partly or wholly of ferric oxide, some of which probably filled cavities from which the lime has been dissolved. The fossil material, much of which consists of broken and water-worn fragments, was evidently gathered by the action of waves and currents into beds and subsequently cemented together by calcium carbonate and ferric oxide. Some clay material has been included in the beds during their formation; this commonly appears as thin seams of shale and argillaceous nodules and lenses.

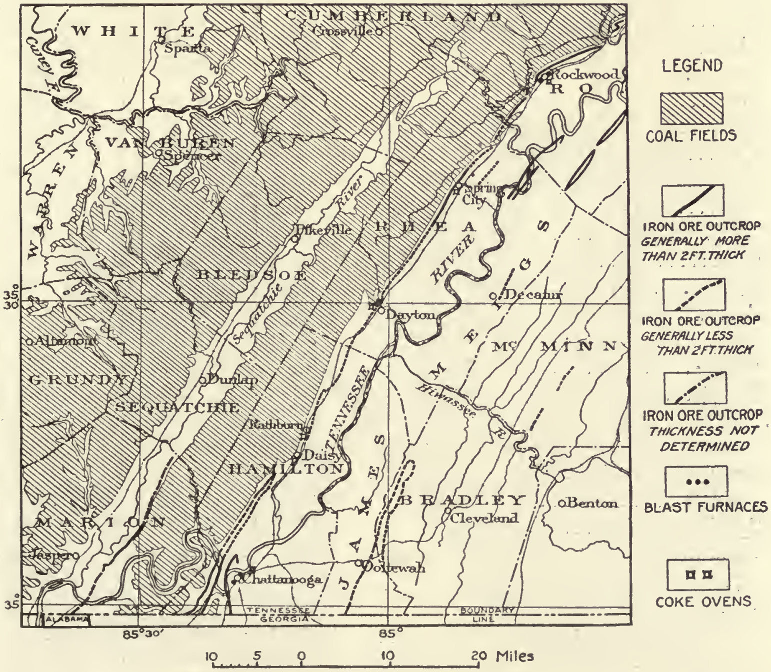


Fig. 146.—Sketch map of iron-ore district near Chattanooga, Tennessee. (*After Burchard, Tennessee Geol. Survey.*)

The granular or oolitic ore consists of aggregates of flat grains with rounded edges like flaxseeds cemented by ferric oxide and calcium carbonate. The flat grains generally have minute nuclei of quartz, about which iron oxide has been deposited. The fossil ore generally predominates in a bed, but in some localities the fossil fragments and the granular bodies are mixed in varying proportions.

Analyses and Specific Gravity Tests of Hard, Semihard, and Soft "Rockwood" Iron Ore from Chamberlain, Tenn.[a]

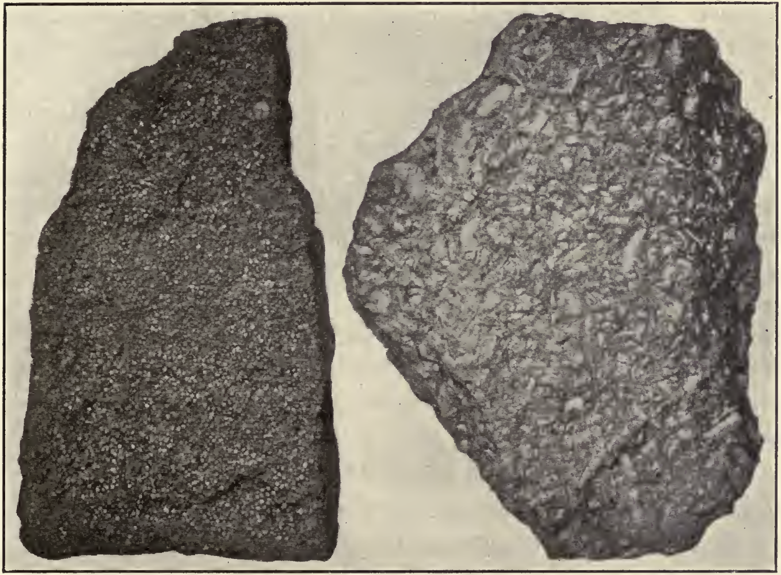
	1	2	3	4
SiO_2	5.00	7.92	7.63	7.62
Al_2O_3	2.82	3.07	3.64	4.31
Fe_2O_3	36.44	50.60	67.60	74.96
FeO	2.20	2.44	4.47	0.10
MgO	1.63	1.71	0.50	0.47
CaO	24.84	13.77	1.68	0.40
Na_2O	0.10	0.10	0.12	0.13
K_2O	0.22	0.25	0.33	0.30
TiO_2	0.11	0.10	0.26	0.12
CO_2	19.89	12.29	3.04	0.32
P_2O_5	0.99	1.31	1.69	1.22
S	0.05	0.05	0.07	0.02
Mn	0.30	0.33	0.58	0.31
H_2O-	0.89	0.59	0.84	0.66
H_2O+	4.72	5.52	8.15	9.35
	100.20	100.05	100.29	100.60
Fe (from Fe_2O_3 and FeO)	27.22	37.32	52.55	50.79
Specific gravity	3.05	3.09	2.49	2.59

[a] Burchard, E. F.: The Red Iron Ores of East Tennessee. Tenn. Geol. Survey *Bull.* 16, p. 76, 1913.

1. Hard ore, large lump, remote from line of division between hard and soft ore.
2. Semihard, small slab, near line of division between hard and soft ore.
3. Soft, small slab, near line of division between hard and soft ore.
4. Soft ore, large lump, remote from line of division between hard and soft ore.

Where weathered by surface waters the lime carbonate is dissolved out of the beds, thereby increasing the content of iron oxide and silica. As in the Birmingham district, such altered ore is termed "soft ore," and the unaltered material is termed "hard ore." The alteration of the ore beds extends from the outcrop down the dip for a few feet to more than 500 feet, the distance depending on the attitude of the beds and the thickness and permeability of their cover. Conditions favoring fairly deep leaching of the ore beds are a rather steep dip and impervious shale at the top and bottom of the ore, which should crop out in a ridge high above the ground-water level. Below the ground-water level the ore is generally hard.

Chemical analyses and specific gravity tests, by George Steiger, of four specimens collected by Burchard illustrate the gradation from hard to soft ore. Solution is attended by an increase in percentages of iron oxide, silica, and alumina and a decrease in lime. With the decrease in lime the minor insoluble impurities, such as manganese, phosphorus, and sulphur, tend to increase proportionally.



Oolitic ore Fossil ore

Fig. 147.—Clinton iron ores from Clinton, N. Y. (*After Burchard, Butts and Eckel, U. S. Geol. Survey.*)

Clinton Region, New York.—The Clinton formation is extensively exposed in western and central New York.[1] Its outcrops are nearly parallel to the south shore of Lake Ontario, and the beds dip gently to the south. Developments are most extensive in Wayne County near Lake Ontario, but mines have also been opened near Clinton and elsewhere in central New

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[1] Newland, D. H., and Hartnagel, C. A.: Iron Ores of the Clinton Formation in New York State. N. Y. State Mus. *Bull.* 123, 1908.

York.[1] As in Alabama, the ores are fossiliferous or oolitic (Fig. 147), and from one to four beds are known. Owing to the nearly flat dips the ores can be mined for considerable distances down the dip by stripping. The workable beds are thin, however, compared to those of Alabama.

Eastern Wisconsin.—Deposits of sedimentary iron ore of the Clinton type are found in Dodge County, Wisconsin,[2] above the Maquoketa shale and below the Niagara limestone. They dip east at low angles, and their horizon is not more than 800 feet below the surface at Lake Michigan, 35 miles east of their outcrop. The ore beds vary in thickness, reaching a maximum of 55 feet. They have been followed 400 feet down the dip and are explored at greater depths by drilling. At many places, according to Thwaites, the ore lenses thin out.

The ore is hydrated iron oxide with 29 to 54 per cent. of iron, averaging perhaps 45 per cent., and is high in phosphorus. Calcite is an abundant gangue mineral. The iron oxide is granular or oolitic, and the granules lie with their flat sides parallel to the bedding of the ore. Some of the granules or aggregates of granules are water-worn. At the top of the iron-bearing member, grading into the oolitic ore, is a bed of hard hematite 6 inches or less in thickness, which is richer in iron than the average ore. The iron minerals were probably deposited as ferric oxide in shallow seas; the worn particles of hematite suggest shore conditions.

TERTIARY ORES OF NORTHEASTERN TEXAS

In northeastern Texas[3] iron ores occur over an extensive area

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[1] Newland, D. H.: The Clinton Iron-ore Deposits of New York State. Am. Inst. Min. Eng. *Trans.*, vol. 40, pp. 165–183, 1910.

[2] Chamberlin, T. C.: "Geology of Wisconsin," vol. 2, pp. 328–334, 1877.

Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 567, 1913.

Thwaites, F. T.: Recent Discoveries of "Clinton" Iron Ore in Eastern Wisconsin. U. S. Geol. Survey *Bull.* 540, pp. 338–342, 1914.

[3] Burchard, E. F.: Iron Ore in Cass, Marion, Morris, and Cherokee Counties, Texas. U. S. Geol. Survey *Bull.* 620, pp. 60–109, 1916.

Penrose, R. A. F., Jr.: The Iron Ores of East Texas. Texas Geol. Survey *First Ann. Rept.*, pp. 65–84, 1890.

Phillips, W. B.: The Iron Resources of Texas. Eng. Soc. Western Pennsylvania *Proc.*, March, 1902, pp. 64–70.

Dumble, E. T., Kennedy, William, and others: Reports on the Iron-ore District of East Texas. Texas Geol. Survey *Second Ann. Rept.* (for 1890), pp. 7–326, 1891.

embracing all or parts of 21 counties. In this area the surface formations consist chiefly of sand, clay, gravel, and silt, predominantly soft or little consolidated. The most recent deposits—those that form the bars, flood plains, and stream terraces—are Quaternary, but the great masses of sand and clay with which the iron-ore deposits are associated are Eocene (Fig. 148).

The principal deposits of brown ore are in two Eocene formations, the Mount Selman formation and the Cook Mountain formation of the Claiborne group. The ore consists chiefly of limonite and iron carbonate. The principal iron-ore deposits are residual, unconsolidated deposits of limonite; nodular, geodal, and concretionary masses of limonite and iron carbonate; and laminated beds of limonite. The nodular and geodal masses of both the brown ore and the iron carbonate are segregated in glauconitic sand and clay in thin lenses and irregular ledges. Unconsolidated material, residual from the breaking down of such masses, is found in many places at the surface. The brown ore occurs also, particularly in central Cherokee County, in a rather persistent laminated bed, 1½ to 4 feet thick.

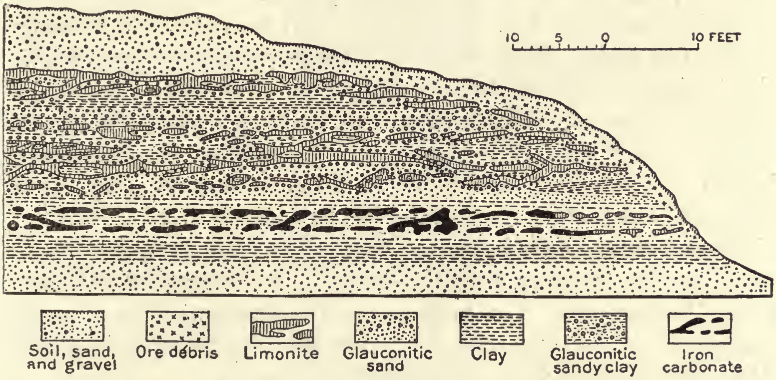

Fig. 148.—Section showing associations of iron ore near Linden, Cass County, Texas. (*After Burchard, U. S. Geol. Survey.*)

IRON CARBONATE ORES OF EASTERN UNITED STATES

Bedded iron carbonate ores are found in the coal measures of western Pennsylvania, northern West Virginia, eastern Ohio, and northeastern Kentucky. Once extensively exploited, they are now mined only in southeastern Ohio, on a small scale.

These ores occur in all the formations from upper Mississippian to Permian, but the most valuable beds are in the Pottsville and Alleghany formations of the lower part of the Pennsylvanian.

According to Harder,[1] the ores are of four classes—limestone ores, block ores, kidney ores, and black-band ores. The limestone ores, which are the most valuable, occur just above or very near the top of a limestone stratum at several horizons. The principal bed is that just above the Vanport or "Ferriferous" limestone, in the lower part of the Alleghany formation. At this horizon ore occurs in many places. The Vanport limestone is as much as 8 or 10 feet thick, and the ore above it ranges from a few inches to several feet. These variations occur within short distances, giving the ore a pockety character. The ore is altered to limonite along the outcrop, and it is mainly the altered portion which has been mined. The limonite ore is usually brown or red and carries 40 to 50 per cent. of iron. The carbonate ore carries from 25 to 40 per cent.

Block ores, so called because they cleave into angular blocks when mined, occur in irregular beds in the Pottsville and Alleghany formations. The beds are more persistent than those of limestone ore, but the ores are leaner and less uniform in grade. Along the outcrop they are altered to limonite.

Kidney ore is iron carbonate which occurs in rounded masses scattered through certain beds of clay and shale. Such masses are abundant in the upper part of the Alleghany formation, occurring at several stratigraphic horizons. They alter to limonite near the weathered surface.

Black-band iron carbonate ore usually occurs in beds interlayered with bituminous shale. As a rule it contains much carbonaceous material. Individual beds of black-band ore are generally only a few inches thick, but in places interbedded bituminous shale and ore occupy zones 10 or 15 feet thick. Black-band ore is richer than the other varieties of iron carbonate.

BROWN ORES OF EASTERN UNITED STATES

The Appalachian valley[2] from Vermont to Alabama is bordered on the east by iron-bearing crystalline rocks which have been exposed to weathering for long periods. In the southern por-

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[1] Harder, E. C.: U. S. Geol. Survey. *Mineral Resources*, 1908, part 1, p, 92, 1909.

[2] Eckel, E. C.: U. S. Geol. Survey *Bull.* 400, p. 145, 1910.

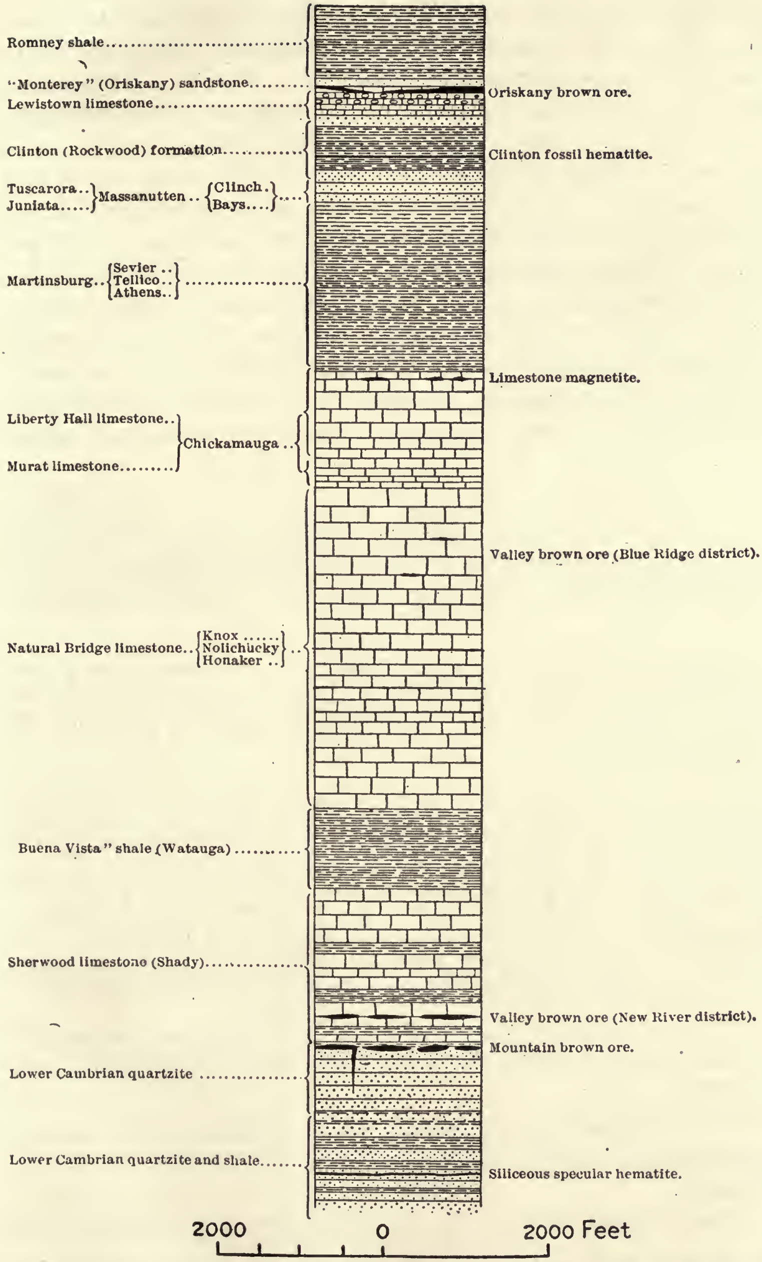

FIG. 149.—Generalized section showing stratigraphic position of several classes of iron ore in the Appalachian region of Virginia. (*After Harder, U. S. Geol. Survey.*)

tion of the valley, from southeastern Pennsylvania to Alabama, there are thick deposits of residual material with which are associated many deposits of brown ore. North of the glacial limit ice erosion has removed iron deposits, and those remaining are merely the basal portions of deposits that were once more extensive. Most of these deposits are in masses of residual material partly or entirely inclosed in solid rock. By far the majority are alteration products of iron carbonate or pyrite, which in turn originated through the replacement of limestone. These ores have a wide geologic distribution (Fig. 149). Many of the brown-ore deposits appear to have been formed rather recently, most of them probably during Tertiary time. Some are associated with residual material derived from Cambro-Ordovician sediments; others associated with later rocks may be epigenetic. According to Eckel, most of the deposits were formed after all the folding of the region had been accomplished, at a period when the topography was substantially similar to that now existing. Evidence of the age of a few of the deposits is afforded also by Tertiary fossils included in or associated with them. At some places the siliceous weathered limonitic material has been concentrated naturally by washing.

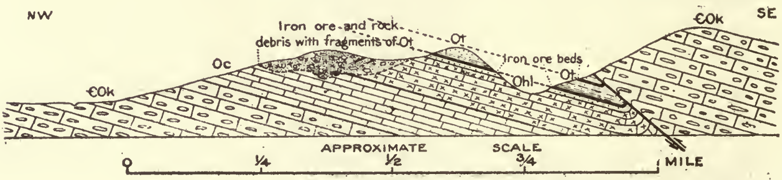

Fig. 150.—Structure section near Sweetwater, Tennessee, showing position of residual iron ore and relation to Tellico ore beds and ferruginous Holston marble to the ore deposit. *ꞒOk*, Knox dolomite; *Oc*, Chickamauga limestone; *Ohl*, Holston marble; *Ot*, Tellico sandstone. (*After Burchard, Tennessee Geol. Survey.*)

At Sweetwater, Tenn., hematite and limonite have accumulated as residual deposits of limestones and associated sedimentary beds (Fig. 150).

At the Gossan lead, Virginia, and at Ducktown, Tenn.,[1] rich limonite ore has been formed through the weathering of iron sulphide.

Small deposits of limonite and hematite in the Appalachian

[1] Emmons, W. H., and Laney, F. B.: A Preliminary Report on the Mineral Deposits of Ducktown, Tenn. U. S. Geol. Survey *Bull.* 470, p. 170, 1910.

region have been formed also as fissure fillings and by the replacement of limestone, quartzite, and shale along fracture zones.[1]

MAGNETITE ORES OF PENNSYLVANIA

At Cornwall, Dillsburg, and several other places in eastern Pennsylvania,[2] large bodies of magnetic iron ores are developed. The region is underlain by sedimentary rocks, which are intruded by Triassic diabase and covered locally by basalt flows. The ores occur at the contact of the diabase with the sediments. The principal deposits lie along the northern edge of the Mesozoic Newark belt, where the diabase is intruded into limestones and limy shales of Cambro-Ordovician age, but locally small deposits are found at the contact of the intrusive masses with Triassic sandstones and shales. In places garnet, pyroxene, epidote, and other heavy silicates form the gangue of the magnetite ore. It is believed that the ores were deposited by solutions that emanated from the diabase and replaced the sedimentary rocks.

MAGNETITE ORES OF NEW YORK AND NEW JERSEY

In the Adirondack region, New York,[3] great deposits of magnetic non-titaniferous ores are associated with metamorphosed sediments and gneisses. The ores occur as rudely tabular bodies parallel to the general structure, though some are elongated and some irregular. They lie along the planes of foliation in the inclosing rocks. These ores are now mined on a large scale and concentrated.

In New Jersey magnetite iron ores which occur in gneisses are believed to be due to magmatic segregation.[4]

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[1] Harder, E. C.: The Iron Ores of the Appalachian Region in Virginia. U. S. Geol. Survey *Bull.* 380, p. 235, 1909.

[2] Spencer, A. C.: Magnetite Deposits of the Cornwall Type in Pennsylvania. U. S. Geol. Survey *Bull.* 359, 1908.

Harder, E. C.: Structure and Origin of the Magnetite Deposits of Dillsburg, Pa. *Econ. Geol.*, vol. 5, p. 599, 1910.

[3] Newland, D. H., and Kemp, J. F.: Geology of the Adirondack Magnetic Iron Ores. N. Y. State Mus. *Bull.* 119, 1908.

[4] Bayley, W. S.: Iron Mines and Mining in New Jersey. N. J. Geol. Survey *Final Rept.*, vol. 7, 1910.

HEMATITES AND MAGNETITES OF WESTERN UNITED STATES

Hartville, Wyoming.—The Hartville iron-bearing district[1] is in the Hartville uplift, a broad, low domical mountain mass in east-central Wyoming. The rocks of the Hartville iron range include steeply dipping pre-Cambrian rocks, flat-lying or gently dipping Carboniferous and Mesozoic rocks, and rocks of Tertiary and Recent age encircling the older rocks and filling depressions of erosion extending into them. The pre-Cambrian rocks comprise metamorphosed sedimentary rocks and igneous rocks and their mashed equivalents. The oldest rocks are an interbedded series of siliceous limestones. The pre-Cambrian sedimentary rocks have been folded into a complex synclinorium whose axis trends east. Above the pre-Cambrian is the Guernsey (Carboniferous) sedimentary formation, and above that the Hartville formation. These formations are encircled by outcrops of the Tertiary rocks of the plains.

The most valuable deposits are lenses of hematite that occur in schist on a limestone foot wall. The ore largely replaces the schist, although in part it fills cavities in the schist which are due to jointing, faulting, and brecciation. Detrital ores of secondary derivation from these deposits are situated at the base of the Guernsey formation, at the base of the Hartville formation, in the Tertiary lake deposits, and in the Pleistocene and Recent stream deposits.

Iron Springs, Utah.—Large deposits of magnetic iron ore are developed at Iron Springs, Utah.[2] The area is occupied by tilted sedimentary rocks including Carboniferous, Cretaceous, and Tertiary limestones. These are intruded by small bodies of diorite porphyry. The magnetite replaces limestone near the igneous contacts and fills fractures in the intrusive rock. The gangue minerals include garnet, diopside, hornblende, and other heavy silicates. The ore available is estimated at 40,000,000 tons.

The intrusive bodies are regular in form, and the sediments surround them in concentric rings. In most places the Carboniferous limestone is in contact with the diorite porphyry,

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[1] Ball, S. H.: The Hartville Iron-ore Range, Wyoming. U. S. Geol Survey *Bull.* 315, p. 190, 1907.

[2] Leith, C. K., and Harder, E. C.: The Iron Ores of the Iron Springs District, Southern Utah. U. S. Geol. Survey *Bull.* 338, 1908.

but locally the diorite breaks through and lies against the Cretaceous rocks. The principal ore deposits are found here and there around the peripheral parts of the intrusives, which stand up as mountains above the surrounding desert. The sediments bordering them occupy the lower slopes. The ores are irregular lenses, the longer diameters of which are generally parallel to the intrusive contacts. Some ore bodies are directly at the contact; others are separated from the diorite porphyry by narrow bands of siliceous contact rock. The deposits are found principally in the Carboniferous limestone, but some occur in the Cretaceous rocks where they are in contact with the diorite porphyry. The contact silicates are associated with the ore, in some places between the ore bodies and the sediments and elsewhere between the ore bodies and the diorite porphyry. In many places around the intrusive masses contact minerals are lacking, and unaltered sediments, such as limestone, occur at the contact.

Eagle Mountain, Calif.—The Eagle Mountain region, California,[1] is an area of ancient gneiss, schist, and quartzite, upon the eroded surface of which was deposited quartzite with lenses of dolomite. These rocks are intruded by great sills of monzonite, and the intrusion was accompanied by an arching up of the sediments into an elongated dome, in the center of which are the older rocks with the associated monzonite. The iron ores are best developed in the sediments on the north and west sides of the dome.

The ores are mainly irregular deposits formed through replacement of the limestone by solutions emanating from the igneous rocks during or soon after their crystallization. The ore is predominantly hematite, probably less than 10 per cent. being magnetite. A considerable proportion of it is very pure and of high grade, containing between 62 and 67 per cent. of iron and less than 0.06 per cent. of phosphorus. The principal gangue minerals are serpentine, mica, amphibole, garnet, epidote, pyroxene, and titanite, which are present in different proportions and occur as large and small irregular masses scattered through the iron-bearing rock. According to Harder, there is probably more than 60,000,000 tons of ore in this area.

Hanover (Fierro) District, New Mex.—The Hanover dis-

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[1] Harder, E. C.: Iron-ore Deposits of the Eagle Mountains, California. U. S. Geol. Survey *Bull.* 503, 1912.

trict, New Mexico,[1] is 2 miles northwest of Santa Rita, occupying a narrow basin along Hanover Creek. Iron ores from the district are smelted at Pueblo, Colo. The sedimentary rocks consist mainly of Carboniferous limestone, which is intruded by a stock of quartz diorite porphyry. The relations are shown by Fig. 151. Here and there along the contacts of the limestone with the porphyry thick garnet zones have been developed.

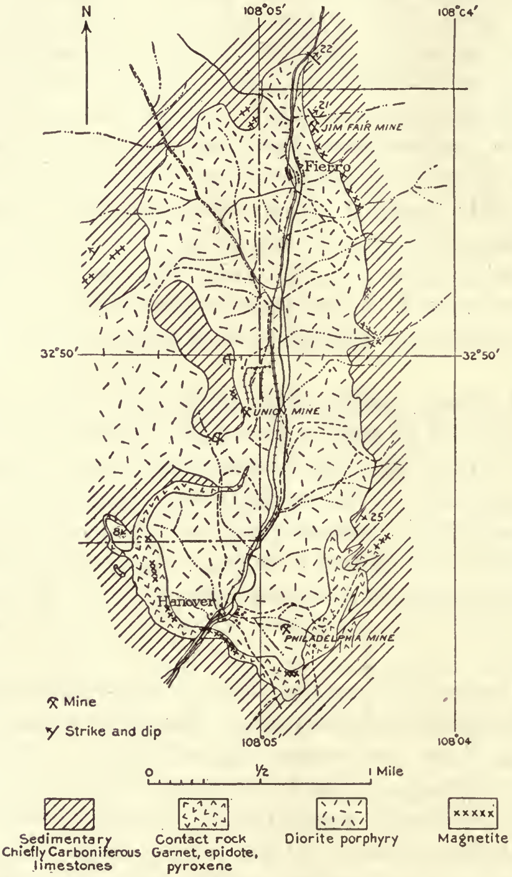

FIG. 151.—Map showing relations of iron-ore deposits to contact, Hanover district, New Mexico. (*After Paige, U. S. Geol. Survey.*)

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[1] PAIGE, SIDNEY: The Hanover Iron-ore Deposits, New Mexico. U. S. Geol. Survey *Bull.* 380, p. 199, 1909.

LINDGREN, WALDEMAR, GRATON, L. C., and GORDON, C. H.: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68, p. 313, 1910.

These zones contain epidote, garnet, and augite, with quartz, calcite, pyrite, magnetite, and zinc blende. The boundary between the contact rock and the sediments is usually sharp; on the outer edge of the zone west of the intrusive mass pyroxene and garnet rock change abruptly to pure limestone. Metamorphism is not confined to the intruded rocks; the diorite porphyry has been altered in less degree by changes of the same nature as those that have affected the limestones.

The ores are arranged about the periphery of the intrusive, nearly everywhere practically at the contact. They are in the main irregular masses of magnetite, with some hematite. At the Union mine they are long compared with their depth and width. Locally the ore carries considerable chalcopyrite. Such ore is left in the mines exploited for iron, but some has been mined for flux and shipped to Arizona smelters. According to Paige the ores were formed by contact metamorphism and related processes, which acted principally on limestones.

Iron Age Deposit, Dale, Calif.—The Iron Age deposit, near Dale, San Bernardino County, California,[1] illustrates a type of ore not yet described. The country rock is an intrusive mass of soda granite and granite porphyry. The ores are chiefly hematite with subordinate magnetite and occur as veins cutting the intrusive granite and granite porphyry (Fig. 152). Garnet and epidote are locally associated with the ore and rocks. The principal iron-ore veins occur over an area about half a mile square; the larger veins, on account of their resistance to erosion, form the summit of a hill.

Iron Mountain and Pilot Knob, Mo.—In St. Francis County, southeastern Missouri,[2] knobs of pre-Cambrian rocks, including porphyry, are surrounded by Cambrian sediments. At Iron Mountain and Pilot Knob considerable iron ore has been mined, the total production being nearly 6,000,000 tons. Iron Mountain was originally thickly covered with loose boulders of iron, and it was at first supposed that the entire hill was ore; but the mining operations disclosed the porphyry below the veneer of rich surface material.

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[1] Harder, E. C., and Rich, J. L.: The Iron Age Iron-ore Deposit near Dale, San Bernardino County, California. U. S. Geol. Survey *Bull.* 430, p. 231, 1910.

[2] Crane, G. W.: The Iron Ores of Missouri. Mo. Bur. Geol. and Mines. vol. 10, 2d ser., pp. 107 *et seq.*, 1912.

The structure of Iron Mountain is domical. The crest of the hill is a porphyry knob which is flanked by Cambrian sediments that rest unconformably upon the porphyry and dip away from it. The ore occurs as huge irregular veins cutting the porphyry, as iron conglomerate at the base of the sedimentary series, and as residual boulders embedded in the clay that once covered the mountain. The veins are in places 60 feet wide and are the sources of the superficial boulder ore and of the conglomerate at the base of the Cambrian. The ore is hard hematite of good grade, in part specular. Some magnetite is present, with quartz, tremolite, and apatite. The iron content ranges from 55 to 67 per cent.

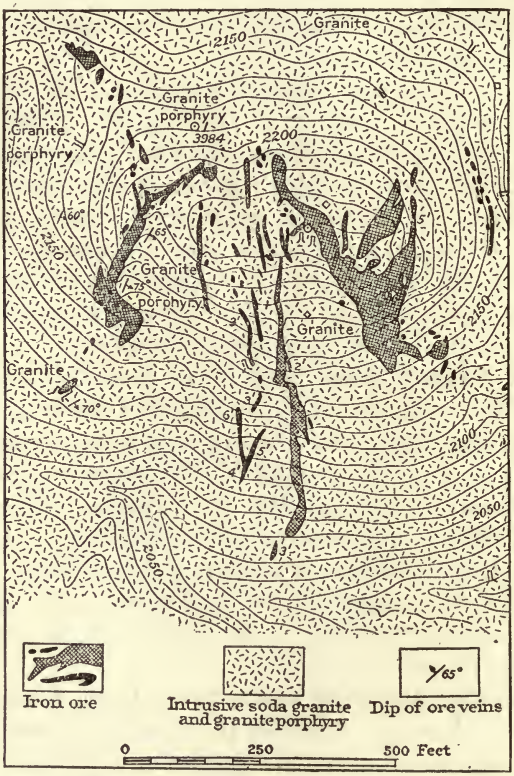

FIG. 152.—Map of Iron Age iron-ore deposits near Dale, California. (*After Harder and Rich, U. S. Geol. Survey.*)

Pilot Knob, near Iron Mountain, is a small mass of porphyry almost surrounded by Cambrian sediments. The iron ore is a rudely tabular body which dips at low angles in the porphyritic rocks (see Fig. 153). Basal Cambrian conglomerates have accumulated near the deposits. These also are worked for iron ore. Boulder ore from the older deposits has accumulated at the present surface.

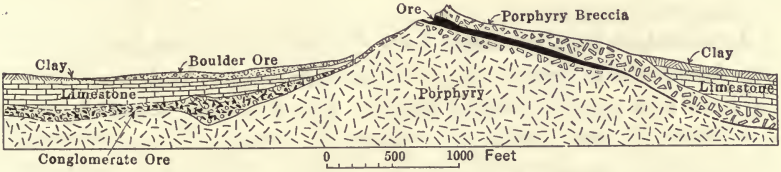

Fig. 153.—Cross-section through Pilot Knob, Missouri, showing relations of ore at three horizons to structure. (*Based on drawing by Potter, Missouri Bur. Geology and Mines.*)

TITANIFEROUS IRON ORES

At many places in the United States there are large deposits of titaniferous magnetite ore.[1] These are not exploited at present, but if certain difficulties in smelting them are overcome they will probably become valuable. Most of these deposits have been formed by magmatic segregation.

Iron Mountain, Wyoming.—The region of Iron Mountain, southeastern Wyoming,[2] about 40 miles northwest of Cheyenne, contains huge deposits of titaniferous iron ore, which, however, are not exploited. The pre-Cambrian complex near the large dike of iron ore at Iron Mountain consists of granular igneous rocks of three varieties—anorthosite (essentially labradorite), the iron ore, and granite. The anorthosite is the oldest of these and is cut by dikes and lenticular masses of iron ore and granite. The deposit of iron ore is a dike 1¼ miles long and 40 to 300 feet wide. At several places it is almost cut in two by wedge-like masses of granite. Through practically its whole length it is bordered on both sides by anorthosite. The contact between

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[1] Singewald, J. T., Jr.: The Titaniferous Iron Ore of the United States. U. S. Bur. Mines *Bull.* 64, 1913.

[2] Ball, S. H.: Titaniferous Iron Ore of Iron Mountain, Wyoming. U. S. Geol. Survey *Bull.* 315, p. 206, 1907.

Lindgren, Waldemar: *Science,* new ser., vol. 16, pp. 984–985, 1902.

Kemp, J. F.: A Brief Review of Titaniferous Magnetites. *School of Mines Quart.,* vol. 20, pp. 352–355, 1899.

Singewald, J. T., Jr.: *Op. cit.*

the anorthosite and the ore, where exposed, is sharp, neither rock having notable gradational borders. The iron ore is a black granular holocrystalline igneous rock, whose constituent grains range from ⅛ to ½ inch in diameter. The greater portion of the iron ore is titaniferous magnetite free from mechanical impurities, but biotite, olivine, and feldspar are sporadically distributed throughout its mass.

Adirondack Region, New York.—The titaniferous iron ores of the Adirondack region, New York, are closely associated with gabbros and nearly related rocks. The principal area of these rocks is in Essex County and southern Franklin County, where they occupy about 1,200 square miles.[1] The largest deposits are in anorthosites—rocks composed essentially of labradorite. The iron ores contain magnetite, ilmenite, a little augite or hypersthene, and garnet; as a rule plagioclase, olivine, hornblende, and apatite are present. The deposits are intruded locally by igneous dikes and together with the gabbro have been subjected to dynamic metamorphism.

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[1] Singewald, J. T., Jr.: The Titaniferous Iron Ores of the United States. U. S. Bur. Mines *Bull.* 64, pp. 47–49, 1913.

Kemp, J. F.: The Titaniferous Iron Ores of the Adirondacks. U. S. Geol. Survey *Nineteenth Ann. Rept.*, part 3, pp. 397–399, 1899.

Newland, D. H.: Geology of the Adirondack Magnetitic Iron Ores. N. Y. State Mus. *Bull.* 119, part 3, pp. 146–170, 1908.

Kemp, J. F., and Ruedemann, Rudolph: Geology of the Elizabethtown and Port Henry Quadrangles. N. Y. State Mus. *Bull.* 138, pp. 137–149, 1910.

CHAPTER XXIII

COPPER

Mineral	Per cent. of copper	Composition
Chalcanthite	25.4	$CuSO_4.5H_2O$
Brochantite	56.2	$Cu_4SO_4(OH)_6$ or $4CuO.SO_3.3H_2O$
Atacamite	59.5	$Cu_2Cl(OH)_3$
Malachite	57.4	$Cu_2(OH)_2CO_3$ or $2CuO.CO_2.H_2O$
Azurite	55.3	$Cu_3(OH)_2(CO_3)_2$ or $3CuO.2CO_2.H_2O$
Chrysocolla	36.0	$CuSiO_3.2H_2O$ or $CuO.SiO_2.2H_2O$
Cuprite	88.8	Cu_2O
Tenorite	79.9	CuO
Melaconite	79.9	CuO
Chalcocite	79.8	Cu_2S
Covellite	66.5	CuS
Bornite	55.5	Cu_3FeS_3
Chalcopyrite	34.6	$CuFeS_2$ or $Cu_2S.Fe_2S_3$.
Enargite	48.3	Cu_3AsS_4 or $3Cu_2S.As_2S_5$.
Tetrahedrite	52.1	$Cu_8Sb_2S_7$ or $4Cu_2S.Sb_2S_3$
Tennantite	57.5	$Cu_8As_2S_7$ or $4Cu_2S.As_2S_3$.

Mineral Composition of Copper Deposits.—Mineralogically the principal copper deposits may be grouped in two classes—(1) deposits composed of sulphides with various gangue minerals and alteration products, and (2) zeolitic native copper ores. In the majority of sulphide deposits chalcopyrite is by far the most common primary copper mineral. In some deposits, however, enargite is the principal primary mineral. Other deposits contain one or more of the minerals chalcocite, covellite, bornite, and tetrahedrite, as primary constituents. Copper sulphide deposits are readily oxidized; near the surface malachite, azurite, chrysocolla, cuprite, chalcanthite, brochantite, and native copper are formed. The principal secondary sulphides in copper deposits are chalcocite and covellite, although secondary bornite and chalcopyrite are not uncommon. As a rule the secondary sulphides are found below the zone of oxidation and their zone grades downward into the primary ores. Zeolitic native copper ores alter very slowly. Near the surface, however, some of them contain some copper as oxides, carbonates, and silicates.

Of the metallic sulphides that are associated with the copper minerals in sulphide deposits, pyrite is practically everywhere present in the primary ores. Many deposits contain sphalerite also, intergrown with pyrite and chalcopyrite. Pyrrhotite is associated with chalcopyrite in some copper deposits. Galena, in subordinate amount, is common.

Of the gangue minerals, some quartz is generally present. Nearly all copper sulphide deposits that replace igneous rocks carry sericite. Ores replacing limestone generally contain calcite. Most contact-metamorphic deposits contain heavy silicates, such as tremolite, actinolite, garnet, and epidote, intergrown with chalcopyrite and other primary sulphides. Copper ores with tourmaline gangue are found in the San Francisco region, Utah, and in some localities in Chile. The great majority of the copper deposits in the United States do not contain sulphates in the gangue of the primary ore, but anhydrite is a gangue mineral in the Cactus mine of the San Francisco region, Utah, and barite is present in the copper ores of Shasta County, California. A little barite occurs also in ores of Butte, Mont.

COPPER PRODUCED IN THE PRINCIPAL DISTRICTS OF THE UNITED STATES TO END OF 1915[a]

District	Date production began	Quantity (pounds)	Percentage of total production	Rank
Butte, Montana	1868	6,680,500,000	31.24	1
Lake Superior, Michigan	1845	5,759,983,236	26.93	2
Bisbee, Arizona	1880	2,025,860,000	9.47	3
Morenci-Metcalf, Arizona	1873	1,221,296,000	5.71	4
Bingham, Utah	1896	1,149,500,000	5.37	5
Jerome, Arizona	1883	753,440,000	3.52	6
Globe, Arizona	1881	683,200,000	3.20	7
Shasta County, California	1897	474,300,000	2.22	8
Ely, Nevada	1908	441,080,000	2.06	9
Ducktown, Tennessee	1850	305,410,000	1.43	10
Santa Rita, New Mexico	1880 (?)	298,911,000	1.40	11
Mineral Creek (Ray), Arizona	....	219,978,000	1.03	12
Foothill belt, California	1862	125,700,000	0.59	13
Tintic, Utah	1880 (?)	124,500,000	0.58	14

[a] BUTLER, B. S.: U. S. Geol Survey, *Mineral Resources*, 1916, part 1, p. 667, 1916.

COPPER PRODUCED IN THE PRINCIPAL DISTRICTS OF THE UNITED STATES IN 1915[a]

District or region	Approximate mine output, pounds	Percentage of total production	Rank
Butte, Montana	267,000,000	17.94	1
Lake Superior, Michigan	238,956,000	16.06	2
Bingham, Utah	165,000,000	11.09	3
Bisbee, Arizona	164,600,000	11.06	4
Globe, Arizona	98,500,000	6.62	5
Alaska (all districts),	70,695,000	4.75	6
Santa Rita, New Mexico	65,000,000	4.37	7
Ely, Nevada	64,638,000	4.34	8
Mineral Creek (Ray), Arizona	60,338,000	4.05	9
Jerome, Arizona	53,260,000	3.58	10
Morenci-Metcalf, Arizona	51,096,000	3.43	11
Shasta County, California	30,500,000	2.05	12
Ducktown, Tennessee	18,205,000	1.22	13
Pioneer, Arizona	6,399,000	0.43	14
Tintic, Utah	5,350,000	0.36	15
Alder Creek, Idaho	4,700,000	0.32	16
Big Bug, Arizona	4,285,000	0.29	17
Lordsburg, New Mexico	3,890,000	0.26	18
Cochise, Arizona	3,815,000	0.26	19
Calaveras County, California	3,700,000	0.25	20
Southwestern Colorado	3,600,000	0.24	21
Pima, Arizona	3,164,000	0.21	22
Plumas County, California	3,000,000	0.20	23
Ophir, Utah	2,212,000	0.15	24
Courtland (Turquoise), Arizona	2,048,000	0.14	25
Placer County, California	1,900,000	0.13	26
Cœur d'Alene, Idaho	1,900,000	0.13	27
Uinta-Summit (Park City), Utah	1,812,000	0.12	28
Leadville, Colorado	1,800,000	0.12	29
New Placers, New Mexico	1,700,000	0.11	30
Goldfield, Nevada	1,670,000	0.11	31
Burro Mountain, New Mexico	1,400,000	0.09	32
Magdalena, New Mexico	1,400,000	0.09	33
	1,407,533,000		
All others	80,467,000		
Grand total	1,488,000,000		

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[a] BUTLER, B. S.: U. S. Geol. Survey, *Mineral Resources*, 1915, part 1, p. 667, 1916.

Minerals found in zeolitic copper ores include native copper, native silver, laumontite, delessite, orthoclase, calcite, thomsonite, quartz, prehnite, analcite, apophyllite, natrolite, and many others. In some deposits sulphides are sparingly associated with these minerals.

Copper Deposits in the United States.—In point of value copper ranks second only to iron among the metals produced in the United States, and the output is greater than the combined output of gold and silver. Operations of mining and beneficiating copper ores are generally more centralized than those of mining and smelting iron ores. Most of the copper ores carry much lower percentages of metal than iron ores, and it is profitable to concentrate them near the producing centers.

Of the copper ores the sulphide deposits are the richest. The Lake Superior region, however, produces copper almost exclusively from native metal ores, which yield an average of about 1 per cent. of copper. Sulphide smelting ores (not concentrated) generally carry 3 to 5 per cent. or more, and concentrating ores from 1 to 3 per cent. At Ducktown, Tenn., however, ores with less than 2 per cent. of copper are smelted. Gold and silver are valuable by-products of many copper ores, and many gold and silver ores carry appreciable amounts of copper.

Genesis of Copper Deposits.—All the larger copper deposits of the United States are epigenetic, thus differing from the larger iron deposits, which are in the main of syngenetic origin. Outside of the United States, however, there are valuable syngenetic copper deposits. The nickel ores of Sudbury, Ontario, which carry as much copper as some copper ores, were formed by magmatic segregation, and the famous copper deposits at Mansfeld, Germany, are probably of sedimentary origin. The great majority of copper deposits, however, the world over, are epigenetic (see Fig. 40, page 91).

The deposits of copper in the United States belong to several genetic groups. Many of them replace limestone, and of these some have been formed under contact-metamorphic conditions by solutions emanating from igneous rocks. Some of the deposits of Morenci, Ariz., and Bingham, Utah, are examples. Other deposits that replace limestone are essentially without contact-metamorphic minerals. As a rule the replacement deposits in limestone do not follow closely well-defined fissures, but many of them are irregular masses or chambers (see page

201). Some, however, are rudely tabular, especially those in which the rock has been replaced along bedding planes. Many copper deposits are veins of the replacement type (see page 242). In these a fissure has become a channel of mineralizing solutions which have replaced the wall rock near the fissure and also filled any openings available. Many such deposits are contained in granites, quartz monzonites, monzonites, or diorites. As a rule these bodies are more nearly tabular than those which replace limestone. Examples of replacement veins of copper ore are found at Butte, Mont., at Globe and Morenci, Ariz., and elsewhere. Primary copper deposits have formed also by deposition from cold solutions (page 74).

The deposits of disseminated copper ores in porphyry and in schists have recently become highly productive. Popularly these are termed the "porphyry" ores. They include huge deposits developed at Bingham, Utah, Ely, Nev., and Santa Rita (Chino), N. M., and some of the deposits at Morenci and Ajo, Ariz., and at Cananea, Sonora, Mexico, as well as many similar deposits in the Southwest. At Miami and Ray, Ariz., disseminated copper ores occur in siliceous mica schists. The disseminated ores in porphyry and in schists include more than half the developed reserves of copper ore within the United States. The bodies of disseminated ore contain many small, irregular, closely spaced veins and veinlets. The country rock between the veins is hydrothermally altered and carries numerous small particles of copper ore, and the entire mass is mined and sent to the concentrators. Nearly all the disseminated or porphyry ore has been greatly enriched by superficial alteration. An outline of the stages involved in the genesis of a disseminated copper deposit in porphyry is given below.

1. Intrusion of a magma and its solidification, forming diorite, monzonite, or granite porphyry.
2. Development of great bodies of fractured or shattered porphyry. As such bodies are not everywhere developed in the porphyry they are probably fractured by stresses rather than by shrinkage due to cooling. Some of the fractures, however, may be cooling cracks.
3. Primary metallization of porphyry by ascending hot waters emanating from deep-seated sources, probably from a related igneous body not yet completely solidified; formation of primary protore consisting of pyrite, chalcopyrite, and other metallic minerals, accompanied by the development of sericite from feldspars and other minerals of porphyry and by the deposi-

tion of quartz. The sulphides fill the minute and closely spaced cracks and are deposited by replacement as shots and small masses between cracks. Copper content of primary ore rarely equals 1 per cent. and is generally not over 0.5 per cent.

4. Top of metallized porphyry body is exposed, by erosion, to weathering. Surface waters dissolve the copper from the rock near the surface, carry it deeper and deposit it in the reducing zone, where oxygen is excluded. The copper is generally deposited as chalcocite, although some bornite, covellite, and chalcopyrite may be deposited. The acid waters alter some of the feldspar and sericite to kaolin and other secondary minerals. The chalcocite zone is a thick blanket-like body lying between the leached zone and primary ore. It is extensive, undulating, and of irregular thickness and grade. The larger and richer ore bodies are in fractured portions of the rock, where downward-moving waters converge.

5. The outcrop, leached zone, and zone of secondary sulphides move gradually downward; as the country is eroded the copper becomes concentrated more and more in the secondary sulphide zone. Pyrite and chalcopyrite are replaced by chalcocite and associated copper sulphides. Locally the primary ore, which generally contains less than 0.5 per cent. of copper, is converted to an ore with 1.5 per cent. or more. The surface zone is leached and generally carries only a little copper; iron oxide is commonly present. As iron is removed from the deposit the leached zone and outcrop become less ferruginous. Much silica may become concentrated with the kaolin at the surface. (For sections of disseminated copper deposits see Figs. 141, 380).

The above outline with some modifications may serve to illustrate the origin of many of the deposits of disseminated copper ores. If the climate becomes arid and the water level is rapidly depressed after the process has gone far, the chalcocite ore may be oxidized largely to cuprite and native copper, or it may be altered to carbonates and silicates near the surface. If the primary ore is comparatively rich in copper and contains little pyrite it migrates less readily and concentrates more slowly, and richer oxidized ores may be exposed at the outcrop and in the oxidized zone, as at Ajo, Ariz. At Miami and Ray, Ariz., the copper ores are developed in siliceous schists that are intruded by granite porphyry. Their secondary concentration is comparable to that of the typical disseminated ores in porphyry. In the descriptions of copper-bearing districts that follow, other exceptional features in several deposits are pointed out. Some districts contain disseminated ores, veins and contact-metamorphic deposits replacing limestone, all in comparatively small areas. In the Southwest there are many comparatively small deposits of copper sulphides that have probably been deposited by cold meteoric waters (see page 77).

Age of Copper Deposits in United States.—Deposits of copper ores in the United States show great range in age. The deposits of Lake Superior, of the Encampment district, Wyoming, of Jerome, Ariz., and of a few other localities in the West are of pre-Cambrian age. These deposits according to Butler,[1] have yielded about 34 per cent. of the output of the United States. In the Appalachian region valuable deposits of copper were formed in Paleozoic time. These include the copper ores of Ducktown, Tenn., and some other deposits, which together have yielded about 2 per cent. of the country's output. Copper deposits were formed also in the Mesozoic era, probably at about the beginning of the Cretaceous. These include the deposits of Shasta County and possibly those of the "foothill belt" in California; also the deposits of Bisbee and probably those of Globe, Ariz. Possibly the deposits of Ray, Ariz., and Ely, Nev., should also be included in this group. The ores of these districts are associated in the main with intrusive masses of granite, diorite, or monzonite and their related porphyries.

The greatest period of copper deposition was in early Tertiary time. The deposits of this period include those of Butte, Mont., Morenci, Ariz., Santa Rita, N. Mex., and probably those of Bingham, Utah, as well as many minor deposits. It is noteworthy that the metalliferous deposits of middle and late Tertiary age in the United States, although they have supplied enormous quantities of gold and silver, have yielded comparatively little copper.

Outcrops of Copper Deposits.—Sulphide ores of copper are almost invariably leached near the surface except where the former surface material has been removed by rapid erosion or by glaciation. Many copper ores, however, contain other metals that are not so readily leached as the copper. Many valuable deposits of copper sulphide ore have been discovered by downward exploitation of oxidized gold and silver ores. Butte, Mont., was first exploited as a gold-placer district; later the upper parts of the veins were worked for silver, and these workings about 200 feet below the surface revealed great bodies of rich copper ores. Deposits at Bingham, Utah (Highland Boy mine), and at Jerome, Ariz. (United Verde mine), were first

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[1] Butler, B. S.: U. S. Geol. Survey. *Mineral Resources*, 1911, part 1, p. 258, 1912.

exploited for gold. Underneath the oxidized gold ores great bodies of copper ore were discovered. The first deposit exploited at Ducktown, Tenn., was worked for iron. At Bisbee, Ariz., the first ores discovered were rich oxidized copper ores. The ores cropped out at one place, from which they were followed downward on the dip, the operations disclosing enormous bodies of sulphide ores, partly oxidized and in the main at the horizon of the ores first discovered. The deposits of Santa Rita, N. Mex., carried rich oxidized copper ore near the surface which passed into sulphide ore below. In regions where copper ores abound areas richly stained with iron are generally considered worthy of exploration in a search for copper. On the other hand, deposits of copper have been found below outcrops that show very little staining by iron oxide. These outcrops, however, are generally silicified and kaolinized.

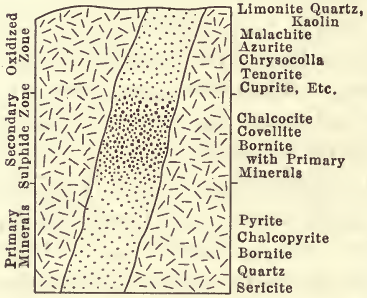

Fig. 154.—Ideal section showing distribution of ore minerals in a copper lode composed of chalcopyrite, bornite, pyrite, quartz, and sericite, after superficial alteration by weathering.

Sulphide Enrichment of Copper Deposits.—Most of the large copper sulphide deposits in the United States show three zones —a leached zone near the surface, an enriched zone below the leached zone, and a zone of lower-grade primary ore below the enriched zone (Fig. 154). In some deposits the oxidized ores and in some the primary sulphide ores are rich enough to work. In other deposits only the ores of the secondary sulphide zone are profitable.

In the oxidized zones of sulphide deposits the mineral waters are sulphuric acid and ferric sulphate solutions. Such solutions dissolve copper readily, and in contact with copper compounds such a system will contain also copper sulphate. The copper sulphate in solution reacts with carbonates or with acid carbonate in solution, precipitating copper carbonates. If chlorides are abundant, copper chlorides may form. In moist countries copper chlorides are unstable. The sulphates chalcanthite and brochantite also may be precipitated, and the basic sulphate brochantite once formed is stable. The silicates of copper are probably formed by copper-bearing solutions reacting on silicic acid, which, as shown by analyses, is commonly dissolved in mine waters. Native copper, cuprite, and tenorite are formed by the reduction or oxidation of various copper compounds. All the copper minerals mentioned above are formed in the main in the oxidized zone, and in sulphide ore deposits their occurrence below this zone is exceptional. None of them are known to be formed in depth by deposition from hot ascending alkaline solutions.

Below the oxidized zone, where air is excluded, copper is precipitated as sulphides: chalcocite, covellite, bornite, chalcopyrite, and possibly some of the more complex antimony and arsenic compounds are formed by these processes. Precipitation may be brought about by chemical interchange with pyrite, chalcopyrite, pyrrhotite, zinc blende, galena, and probably with some other sulphides, the process being mainly metasomatic replacement. The copper sulphides are precipitated also by hydrogen sulphide, which may be generated by attack of acid solutions on several of these sulphides. The chalcocite that forms under these conditions may be a fine dust-like powder, termed "sooty chalcocite," but much of it is fine massive glistening material. In a reducing environment the copper sulphides are highly stable. Iron sulphide is dissolved in acid even in a reducing environment. The double sulphides of iron and copper would probably not be precipitated from acid solutions that contained much copper. As the solutions descend, however, they lose acidity, and copper sulphide is precipitated at the expense of iron sulphide, the iron going into solution. A decrease in acidity, a decrease in copper, and an increase of iron in solution bring about a state of equilibrium which is increasingly favorable to the precipitation of double sulphides, such as chalcopyrite and bornite.[1]

In the oxidizing zone copper is much more soluble than gold, and, unlike gold, it may be dissolved in the absence of chlorides in sulphate solutions. Thus many deposits which contain both copper and gold show a distinct segregation of gold near the surface, while copper ores with subordinate gold are found lower down. Even where the conditions for the solution of gold are most favorable it is probably precipitated mainly in the upper part of the chalcocite zone. It would not remain in solutions

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[1] Wells, R. C.: The Fractional Precipitation of Sulphides. *Econ. Geol.*, vol. 5, pp. 12–13, 1910.

that contained much ferrous sulphate, and chalcocitization is probably attended by the generation of abundant ferrous sulphate. Ferrous sulphate precipitates silver also, and silver is reprecipitated by chalcocite very readily in both neutral and acid solutions (see page 443).

In pyrrhotite ores chalcocite enrichment is shallow. In deposits of sphaleritic copper ores without pyrrhotite the chalcocite zone may be moderately extensive vertically. The most extensive chalcocite zones are in pyrite and chalcopyrite deposits that do not contain pyrrhotite. Most of them also contain little or no sphalerite (Fig. 155).

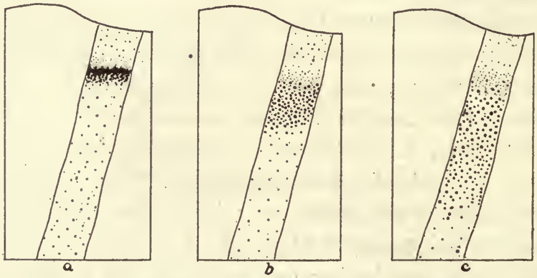

Fig. 155.—Diagrams showing influence of mineral composition of copper lodes on depth of enrichment. *a*, Minerals react rapidly with copper sulphate solutions and deposit copper sulphides; *b*, minerals react less rapidly; *c*, minerals react slowly.

Carbonates react with acid solutions and tend to delay the downward migration of copper. If there is much lime carbonate in the gangue of the ore or in the wall rock, the downward migration of metallic sulphates may be checked.

A zone of chalcopyrite enrichment may exist below a chalcocite zone. Some profitable ores of copper are found below the zone of chalcopyrite enrichment, but these are not ordinarily "bonanza" ores.[1]

COPPER MINERALS

Native copper in zeolite ores is primary (see page 395). In sulphide deposits it is invariably formed by secondary processes. In some sulphide deposits it is a valuable constituent of the ore

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[1] For additional data relating to the influence of gangue and ore minerals on depth of secondary sulphide zones, see Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, pp. 172–175, 1917.

bodies occurring above the chalcocite zone or in the upper part of the chalcocite zone.

Chalcanthite, blue vitriol, is present in many oxidized zones as efflorescences or stalactites on walls of open fissures, or as veinlets filling small crevices above the upper limit of the zone of secondary sulphides.

Brochantite has been identified in only a few deposits but is probably not uncommon. It is frequently mistaken for carbonates. Brochantite is unknown in the deeper levels of sulphide lodes.

Atacamite, the oxychloride of copper, is not stable in most climates. In arid countries it forms in the oxidized zones. It has lately been shown that much of the material of Chuquicamata, Chile, formerly supposed to be atacamite is brochantite.

Malachite and azurite are abundant in the oxidized zones of many cupriferous deposits, especially in deposits that are inclosed in limestone.

Chrysocolla occurs abundantly in the outcrops and near the surface of some copper deposits; in others it is rare or absent. It is a common mineral also in the oxidized zones of some silver and gold mines. It is in places associated with malachite and azurite and is not known as a deposit of ascending hot waters.

Cuprite is a common mineral of the oxidized zones of deposits of copper sulphides and is probably secondary in all its occurrences. At Morenci, Ariz., according to Lindgren,[1] it is an oxidation product of chalcocite.

Tenorite, the crystalline form of the black oxide of copper, is much less abundant than cuprite. The earthy, sooty variety is known as melaconite.

Copper pitch ore is a secondary material of complex character and somewhat uncertain composition. A sample from the Detroit mine in the Morenci district, Arizona,[2] showed oxides of copper, zinc, and manganese, with considerable water and silica.

Chalcocite, copper glance, is the most valuable copper mineral. In most of its occurrences it is clearly of secondary origin (see page 155), for it replaces other minerals metasomatically or occurs as veinlets in small cracks in the primary ore. Many examples

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[1] LINDGREN, WALDEMAR: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 43, p. 111, 1905.

[2] *Idem*, p. 114.

are known of its replacement of pyrite, zinc blende, and galena. In many deposits exploration extends below chalcocite into the lower-grade primary sulphide ore, which generally consists of chalcopyrite, pyrite, and other minerals without chalcocite.

The replacement of pyrite by chalcocite[1] is, according to Stokes, effected as follows:

$$5FeS_2 + 14CuSO_4 + 12H_2O = 7Cu_2S + 5FeSO_4 + 12H_2SO_4.$$

In a few districts chalcocite is primary.[2]

Some chalcocite deposits in sandstone and shale, widely distributed in the Southwest, are in areas remote from igneous rocks and appear not to be related genetically to igneous processes. They have doubtless been deposited by cold waters and some of them have replaced coal or other organic material. Although these deposits are not secondary in the sense that they have been formed generally at the expense of older sulphides, the conditions under which they were formed as regards temperature, pressure, and concentration of solution are probably near those which prevail in processes of sulphide enrichment.

Covellite is found in small amounts in many mining districts of North America but is not abundant in many of the larger deposits. As a rule it is associated with chalcocite, and it is formed chiefly by the replacement of iron or zinc sulphides. As the precipitation of cupric sulphide from cupric sulphate solutions involves no change of valence, some simple equations may be written:

$$ZnS + CuSO_4 = CuS + ZnSO_4.$$
$$CuFeS_2 + CuSO_4 = 2CuS + FeSO_4.$$
$$FeS + CuSO_4 = CuS + FeSO_4.$$
$$H_2S + CuSO_4 = CuS + H_2SO_4.$$

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[1] STOKES, H. N.: Experiments on the Action of Various Solutions on Pyrite and Marcasite. *Econ. Geol.*, vol. 2, p. 22, 1907.

SPENCER, A. C.: Chalcocite Deposition. Wash. Acad. Sci. *Jour.*, vol. 3, p. 73, 1913.

ZIES, E. G., ALLEN, E. T., and MERWIN, H. E.: Some Reactions Involved in Secondary Copper Sulphide Enrichment. *Econ. Geol.*, vol. 11, pp. 407–503, 1916.

[2] LANEY, F. B.: The Relation of Bornite and Chalcocite in the Copper Ores of the Virgilina District of North Carolina and Virginia. *Econ. Geol.*, vol. 6, pp. 399–411, 1911.

Bornite is found in associations that indicate its formation under many different geologic conditions. It occurs in lodes that were formed at great depths and also in some that were formed at moderate depths, and less abundantly in deposits remote from outcrops of igneous rocks.[1] It is deposited on pyrite and other sulphides by cold copper sulphate waters, and in some deposits it is a valuable secondary sulphide. As such it is usually much less abundant than chalcocite.

Chalcopyrite in the greater number of its occurrences is clearly primary, and in many sulphide deposits it is the only important primary copper mineral in the unaltered ore. A list of occurrences of primary chalcopyrite would include nearly all important deposits of copper ore in the United States. It is, however, secondary in many deposits. In general it forms at greater depths than secondary chalcocite.

Enargite is an ore mineral of great value at Butte, Montana, is present in considerable amounts at Tintic, Utah, and occurs in less abundance in several other districts. It is in the main, primary.

Famatinite is not a common ore of copper, and little is known as to its origin. In view of the primary origin of enargite, its corresponding arsenic salt, it is probably primary.

Tetrahedrite is a comparatively common copper mineral. In most of its occurrences it is primary.

Tennantite is the arsenic salt corresponding to tetrahedrite, but it is not so common as tetrahedrite.

COPPER-BEARING DISTRICTS

Butte, Mont.—The Butte district, in western Montana, is the most productive copper district in the world. It has yielded over 7,000,000,000 lb. of copper, more than 300,000,000 ounces of silver and 1,500,000 ounces of gold, also much zinc and smaller amounts of arsenic, lead and manganese. Developments extend to depths greater than 3,000 feet, where ores of good grade are found. The copper ore is concentrated or smelted directly in the great plants at Anaconda, Great Falls, and Butte.

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[1] Lindgren, Waldemar, Graton, L. C., and Gordon, C. H.: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68, pp. 77–78, 1910.

COPPER AND ASSOCIATED METALS PRODUCED IN BUTTE DISTRICT, MONTANA, 1913–1915[a]

Year	Copper pounds	Yield, copper, per cent.	Gold ounces, per ton	Silver ounces, per ton
1913	283,600,000	2.70	0.0058	1.92
1914	235,700,000	2.66	0.0059	1.83
1915	267,000,000	2.65	0.0066	1.82

[a] BUTLER, B. S.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 700, 1916.

The Butte district[1] is an area of quartz monzonite (frequently called granite), which is intruded by a later aplite, and by rhyolite porphyry. Dikes of late Tertiary rhyolite cut the granite, and effusive rhyolite rests upon it. In the western part of the region are Tertiary lake beds more recent than the granitic rocks. These are composed of sand, gravel, and water-laid tuff.

The quartz monzonite, aplite, and porphyry, which contain all the ores, are phases of the great Boulder batholith, which extends some 64 miles southward from a point near Helena and is 12 to 16 miles wide. This batholith intrudes Paleozoic and Cretaceous sedimentary rocks and along its borders has induced

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[1] WEED, W. H., EMMONS, S. F., and TOWER, G. W., JR.: U. S. Geol. Survey *Geol. Atlas*, Butte folio (No. 38), 1897).

WEED, W. H.: Geology and Ore Deposits of the Butte District, Montana. U. S. Geol. Survey *Prof. Paper* 74, 1912.

WINCHELL, H. V.: Synthesis of Chalcocite and Its Genesis at Butte, Montana. *Eng. and Min. Jour.*, vol. 75, pp. 782–784, 1903.

SALES, R. H.: Ore Shoots at Butte, Montana. *Econ. Geol.*, vol. 3, pp. 326–331, 1908; Superficial Alteration of the Butte Veins. *Idem*, vol. 5, pp. 15–21, 1910; Ore Deposits of Butte, Montana. Am. Inst. Min. Eng. *Trans.*, vol. 40, pp. 3–106, 1914.

SIMPSON, J. F.: The Relation of Copper to Pyrite in the Lean Copper Ores of Butte, Montana. *Econ. Geol.*, vol. 3, pp. 628–636, 1908.

KIRK, C. T.: Conditions of Mineralization in the Copper Veins at Butte, Montana. *Econ. Geol.*, vol. 7, pp. 35–82, 1912.

RAY, J. C.: Paragenesis of the Ore Minerals in the Butte District, Montana. *Econ. Geol.*, vol. 9, pp. 463–481, 1914.

LINFORTH, F. A.: Applied Geology in the Butte Mines. Am. Inst. Min. Eng. *Trans.*, vol. 46, pp. 110–127, 1914.

BARD, D. C., and GIDEL, M. H.: Mineral Associations at Butte, Montana. Am. Inst. Min. Eng. *Trans.*, vol. 46, pp. 123–127, 1914.

ATWOOD, W. W.: The Physiographic Conditions at Butte, Montana, and Bingham Canyon, Utah, when the Copper Ores in These Districts were Enriched. *Econ. Geol.*, vol. 11, pp. 697–741, 1916.

contact metamorphism by which the typical garnet zones have been developed in the calcareous sediments. There are, however, no metamorphosed sediments in the Butte mining district.

Although the rocks of the batholith are in general of comparatively uniform composition, the Butte quartz monzonite is a somewhat more basic phase. The aplite represents a differentiation product that was forced into cracks in the quartz monzonite after that rock had cooled.

There seems to be a genetic relation between the copper ores and the porphyry intrusives. The porphyry is found mainly in the eastern portion of the copper area, where it is younger than the Butte quartz monzonite and older than the veins, for even, the oldest veins cut through it. The veins in the porphyry as in the aplite, are narrower and poorer than in the quartz monzonite. The porphyry is, however, the youngest igneous rock exposed that is older than the oldest veins.

The copper ores are included in an area about 1½ miles long and a mile wide, and this area is almost surrounded by a much larger area containing closely spaced silver-bearing veins. Pronounced parallelism is noticeable in veins of both groups.

The fissuring in the district is exceedingly complex (Figs. 156, 157). The systems as outlined by Sales are (1) Anaconda system; (2) Blue system of fault fissures; (3) Mountain View breccia faults; (4) Steward system; (5) Rarus fault; (6) Middle faults; (7) Continental fault.

1. The Anaconda system is composed of easterly fissures which are generally heavily mineralized and along which there has been but little displacement. In general they dip south at high angles. In the copper-producing area there are two notable groups of veins belonging to the Anaconda system. On the south or Anaconda group are the deposits of the Gagnon, Original, Parrot, Never Sweat, Anaconda, St. Lawrence, Mountain View, Leonard, West Colusa, and other mines. North of this group and separated from it by a comparatively barren area is the second group, which includes the Syndicate, Bell, Speculator, and associated fissures. Some of the easterly fractures are joined by many closely spaced smaller fractures, doubtless of the same age. They strike about N. 20° W. Many of them play out toward the southeast or join other fractures. They form altogether a network having what Sales has designated "horse-

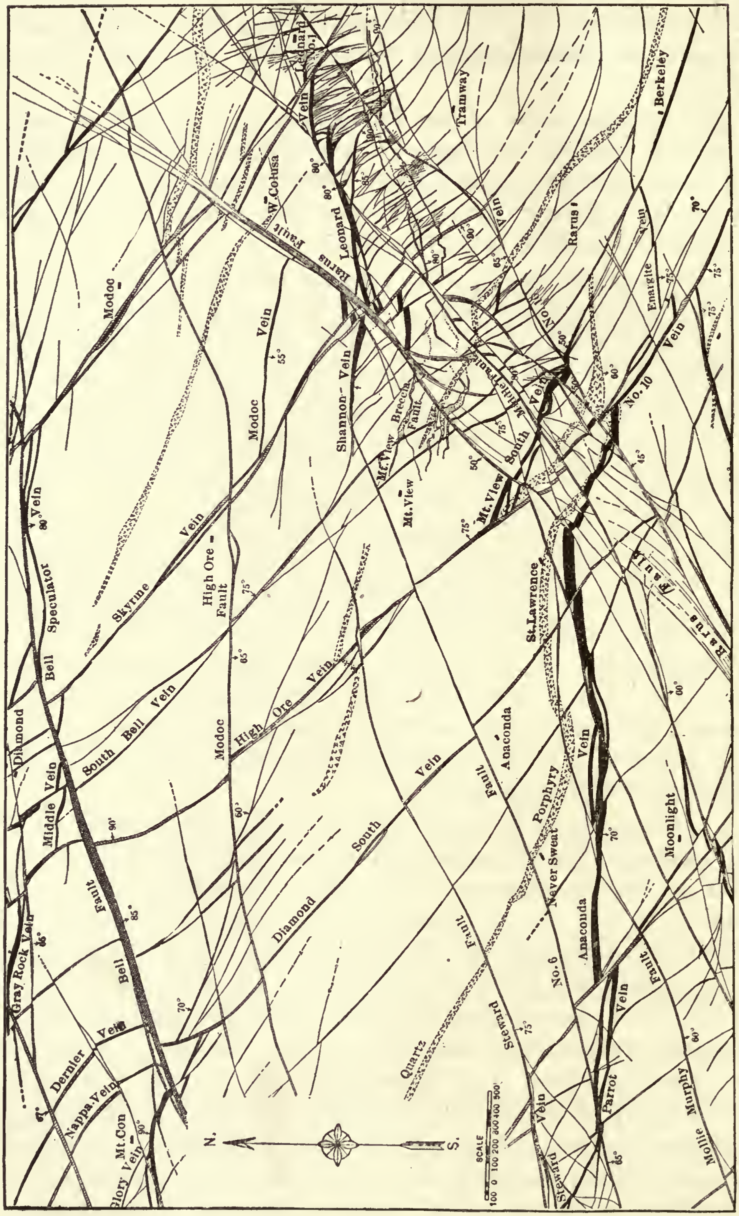

FIG. 156.—Horizontal section of part of Butte district, Montana, 4600 feet above sea level (about 1500 feet below the surface). (*After Sales.*)

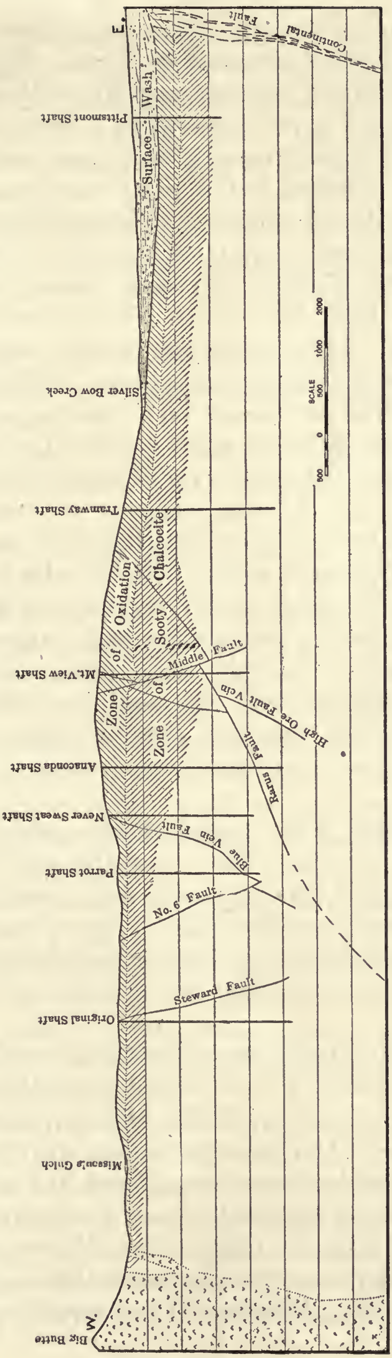

FIG. 157.—Vertical section of Butte district, Montana, along Anaconda vein. (*After Sales.*)

tail" structure. In some mines the most valuable ore bodies are along these northwest conjugated fractures. They are well developed in the Tramway, Leonard, and West Colusa mines, where large ore bodies are stoped from them. North of the copper-bearing area are the great easterly silver and zinc lodes. These also are believed to belong to the Anaconda system of fissures.

2. The Blue system is composed of several fissures that strike northwest. These cross and fault the veins of the Anaconda system. Members of the Blue system include the Clear Grit, Blue, Diamond, High Ore, South Bell, Skyrme, Edith May, and other veins. These veins are spaced with considerable regularity and show regular strike lines, although they differ greatly in dip. The prevailing dip, however, is to the southwest. The fissures are faults, many of which have displacements of 150 to 300 feet. The grooves in the fault planes are generally rather flat-lying, and the displacements are nearly horizontal shifts to the northwest on the northeast sides of the fault fissures. Although the movements of the hanging walls have downward components as well as horizontal components, owing to the larger amount of horizontal movement the faults appear on sections as "reverse" faults. The lodes of the Blue vein system carry large deposits, although they are much less valuable and less uniformly mineralized than the easterly veins, on which the deposits are almost continuous except where displaced by faults.

3. The Mountain View breccia faults, which are notably developed in the Mountain View, Leonard, and Gagnon mines, are persistent fissures filled with angular or rounded fragments of country rock and of earlier veins. They strike about N. 75° E. Near veins they contain locally enough brecciated ore to be worked. They are later than the deposits of the Blue vein system.

4. The Steward system includes fault fissures that strike about N. 65° E., dip about 65° S., and extend across the Butte district. They include the Rob Roy, Mollie Murphy, Steward, Modoc, and Poser fissures. The Steward fissures are in general planes of movement. Displacements range from 50 feet or less to 150 feet. As a rule the hanging wall moved downward in these faults at an angle of 70° with the strike. Few of them carry much ore.

5. The Rarus fault is a complex fissure that is later than the Anaconda, Blue, and Mountain View systems. It is known

also to be later than some of the veins of the Steward system. It strikes northeast and dips 45° NW. It is a broad crushed zone from 20 to 250 feet wide and is limited by tabular masses of fault gouge from 1 to 8 inches wide. The displacement is not uniform. In the northeastern part of the district it is small; in the southwestern part it is as much as 350 feet. The hanging wall at some places moved downward on the dip, but in the Leonard mine the movement was at angles of 60° with the strike or less. The ore in the Rarus fault is drag ore from older veins.

6. The Middle faults, as developed in the Mountain View mines, represent a period of movement later than the Rarus. They are not mineralized.

7. The Continental fault, which is on the east edge of the mineralized area, is likewise later than the metallization of the district.

The relations of the fracture systems to one another are stated above. The earliest or easterly fracturing followed the consolidation of aplite and quartz porphyry. The rhyolitic intrusion was subsequent to the earlier vein fissures; the silver veins are cut off, in places cut in two, by intrusive dikes of rhyolite. Hydrothermal alteration of the quartz monzonite is extensive. Where large veins are closely spaced the entire area of quartz monzonite is hydrothermally altered; where the veins are less closely spaced fresh rock is found between them. Kirk recognizes two phases of alteration—an earlier chloritic phase and a later sericitic phase.

The veins are replacement deposits, and, according to Sales, 60 to 80 per cent. of the ore is altered quartz monzonite with disseminated sulphides. The ores are of three classes—copper, siliceous silver, and zinc. The copper ores contain a little silver; the silver ores rarely contain much copper; both copper and silver ores contain a little gold, and the high-grade silver ores contain it in notable amounts.

Chalcocite, enargite, and bornite are the most common copper minerals. Covellite occurs in large amounts in the Leonard mine and in small amounts in others. Chalcopyrite is present in workable quantities in a few properties but is an insignificant part of the total copper-ore output. Tetrahedrite is found in the deep workings of a few mines. Chalcanthite is common in the old workings. Pyrite is the most common sulphide. It is estimated by Weed that since the beginning of mining about 75 per cent. of the copper produced has come from glance, 20 per cent. from enargite, 4 per cent. from bornite, 0.5 per cent. from covellite, and 0.5 per cent. from chalcopyrite.

Native silver occurs in the copper ores, especially in those from the upper levels. Ruby silver and indeterminable black sulphantimonites and sulpharsenides occur in the siliceous silver ores. Free gold is rare but occurs in some silver ores. The gangue minerals include quartz, sericite, and several residual minerals of the altered country rock. Much rhodonite and rhodochrosite and some fluorite occur in the silver and zinc ores.

Sales states that there is a central zone of copper ore, mainly chalcocite and enargite, which grades into an intermediate zone that contains ores with the same minerals and also sphalerite, rhodochrosite, and rhodonite, with a slight increase of silver content. In an outer or peripheral zone the ores carry sphalerite, rhodonite, rhodochrosite, tetrahedrite, tennantite, and chalcopyrite, but rarely chalcocite or bornite. Their chief metals are silver, gold, zinc, and some lead.

The oldest lodes, including the Parrot, Anaconda, and Syndicate, occupy openings along which there was but slight tangential movement. They have been fractured, however, since the ore was deposited. The ore minerals in these lodes consist chiefly of pyrite, chalcopyrite, chalcocite, and covellite. According to Sales they contain some enargite also.

The veins of the Blue system contain the minerals named as constituents of the earlier veins and large quantities of enargite. Along these veins evidence of movement parallel to the planes of the deposits is pronounced. Although the mineral composition of the veins is comparatively uniform, the later fissures are characterized by barren patches separating rich ore shoots. These ore shoots, as shown by Sales, are of primary origin, the course of the mineralizing solutions having been determined by fault gouge, which effectively dammed back the waters from the portions of the fissures that are barren.

Some silver lodes crop out conspicuously, but the outcrops of copper lodes are not prominent. The leached zone extends downward in places 300 or 400 feet below the surface. It contains silver, locally 30 ounces or more to the ton, but little copper. Below the oxidized zones of copper lodes, grading into them locally within 2 or 3 feet, are enormous masses of chalcocite, with some bornite and covellite. This ore carries in general 2 or 3 ounces of silver to the ton.

In the great ore bodies of the upper levels of the Anaconda veins chalcocite occurred in nearly pure masses 20 feet or more wide. In depth the mineral shows a more crystalline structure, and it is found in all the mines in greater or less abundance and purity, but as a rule it forms small grains scattered through the ores. The chalcocite ores are present in large quantities also between the 2,000- and 3,000-foot levels.

Emmons, Weed, and many others who studied the copper lodes in the earlier stages of their development regarded the chalcocite ores as secondary deposits formed by descending waters. More recent investigations, including those of R. H. Sales and his associates, have shown that the deeper chalcocite ores are primary.

Bingham, Utah.—The Bingham district, Utah, is in the Oquirrh Range about 20 miles southwest of Salt Lake City. In 1915 the district produced 165,000,000 pounds of copper. Its measured reserves of copper ore are probably the largest in the United States. It has produced also large amounts of silver, lead, and gold.

The Bingham district[1] is an area of Carboniferous quartzites and limestones intruded by monzonite and monzonitic porphyry and covered in part by andesites, andesitic porphyries, and breccias. The quartzite series ("Bingham quartzite") is several thousand feet thick. It contains at least seven limestone lenses, some of them 300 feet thick.

The region is crossed by many faults and fissures which trend in all directions. The faults are both normal and reverse, and some carry ore. Extensive fissuring and some faulting has taken place also after the deposition of the ores.

The ore deposits are in or near the intrusive monzonite or monzonitic porphyry. They include fissure veins in several formations, bedding-plane replacement deposits in limestone, and disseminated deposits in shattered porphyry. Boutwell

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[1] Boutwell, J. M.: Economic Geology of the Bingham Mining District, Utah. U. S. Geol. Survey *Prof. Paper* 38, 1905.

Beeson, J. J.: The Disseminated Copper Ores of Bingham Canyon, Utah. Am. Inst. Min. Eng. *Bull.* 107, pp. 2191–2236, 1916.

Atwood, W. W.: The Physiographic Conditions at Butte, Montana, and at Bingham Canyon, Utah, when the Copper Ores in These Districts were Enriched. *Econ. Geol.*, vol. 11, pp. 697–741, 1916.

recognized two periods of mineralization—one during the intrusion of the monzonite porphyry, and a second closely following the solidification and fracturing of the porphyry. The ore bodies that were most productive in the earlier history of the district are large replacement deposits of sulphide ore in limestone. These ores consist chiefly of pyrite, chalcopyrite, sphalerite, and chalcocite, with a little bornite and enargite and oxidation products. In many of the deposits a little pyrrhotite is present, and in some ore from the Highland Boy mine pyrrhotite is abundant.

On the borders of the great ore body of the Highland Boy, which partly replaces a limestone lens, garnet and specularite are intergrown with calcite, chalcopyrite, and sphalerite. This ore body was formed under contact-metamorphic conditions; the heavy silicates, however, are not conspicuously developed.

The ores of the Highland Boy mine near the surface were extensively oxidized and carried concentrated gold. The mine was first exploited for gold, but deeper developments disclosed great bodies of copper ore containing gold and silver. The copper ores carry little chalcocite and are in the main primary.

The argentiferous lead ores are deposits of galena that generally carry a high content of silver. They occupy veins in igneous and sedimentary rocks and replace limestone.

Another type of deposit which in recent years has become highly productive contains copper ore disseminated in monzonite porphyry. The principal deposit of this type is in the intrusive body at Upper Bingham. The mineralized tract contains a multitude of thin unsystematized parting planes. The rock is bleached, silicified, and sericitized in and near the areas of great shattering. The copper content is lowest in the oxidized zone at the surface. Farther down, in the unoxidized rock, the secondary sulphide ore consists of chalcocite, covellite, and chalcopyrite. It lies in scales and films in silicified walls of cracks, and in areas of great shattering it occurs abundantly on quartz-coated cracks and is disseminated through the silicified bleached walls. Quartz, sericite, brown mica, and some orthoclase[1] in

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[1] Butler, B. S.: U. S. Geol. Survey *Mineral Resources*, 1912, part 1, p. 325, 1913.

this ore are later than the original rock-making minerals. The deposit lies like a thick blanket. Below it the porphyry carries pyrite and chalcopyrite but is of too low grade to work.

The Utah Copper Co., which is exploiting the disseminated ores of Bingham, has developed about 338,000,000 tons, the average content of which is about 1.5 per cent. of copper and from 20 to 30 cents a ton in gold and silver. The surface of this ore body covers 211 acres, and the average thickness of the workable ore is probably about 414 feet.

Metals Produced by Utah Copper Co., 1913–1915

Year	Ore milled, short tons	Copper content, per cent.	Mill recovery, per cent.	Refined copper, pounds	Gold and silver per pound of copper, cents	Cost per pound of copper, cents
1913	7,519,392	1.25	63.95	113,942,834	0.64	9.498
1914	6,470,166	1.42	66.04	115,690,445	0.75	8.131
1915	8,494,300	1.43	64.13	148,397,006	0.62	7.560

The leached capping, which is stripped by steam shovels, has an average thickness for the entire area of 110 feet (see Fig. 67, page 141). The average depth of the bottom of the deposit now workable is about 530 feet below the surface, although in places it extends downward more than 900 feet. In much of the ore, especially in that of lower levels, chalcopyrite is abundant, and considerable masses of the ore carry very little chalcocite, chalcopyrite and covellite being the principal minerals. The Utah Copper Co. produces annually from the disseminated copper ore more than a million dollars in precious metals, about four-fifths of which is gold and about one-fifth silver. This is equivalent to about 22½ cents per ton of ore and 1.07 cents per pound of copper.

The Ohio Copper Mining Co. mines ores disseminated in fractured quartzite near the Upper Bingham intrusive mass.

Bisbee, Ariz.—The Bisbee (Warren) district, Arizona, is situated in the Mule Mountains, a low range in the southeast corner of the State.

Production in this district began in 1880, and to the end of 1915 it had yielded 2,025,860,000 pounds of copper. The oldest

COPPER PRODUCED IN BISBEE DISTRICT, ARIZONA, 1913–1915[a]

Year	Quantity, pounds	Average yield per ton in copper, per cent.	Value in gold and silver per ton
1913	155,100,000	5.6	$1.16
1914	151,600,000	5.4	1.35
1915	164,600,000	5.0	1.66

[a] BUTLER, B. S.: U. S. Geol. Survey, *Mineral Resources*, part 1, p. 674, 1916.

rocks[1] of the district belong to the Pinal schist, of pre-Cambrian age. The granite mass of Juniper Flat, north of Bisbee, which is intruded into the schist, is also pre-Cambrian. Resting unconformably on the schist is the Cambrian Bolsa quartzite with a basal conglomerate and above the quartzite, are several limestone beds with an aggregate thickness of over 4,000 feet. These rocks include the Abrigo, Martin(?), Escabrosa, and Naco limestones. They were intruded in early Mesozoic time by stocks, dikes, and sills of granite porphyry and, after deep erosion, were covered by a thick series of Cretaceous (Comanche) beds. These have in greater part been eroded from the productive area.

The district is cut by numerous faults, some older and some younger than the Cretaceous beds. In some of the tilted fault blocks the strata are gently folded (Fig. 158).

The primary ores were deposited during or after the intrusion of the granite porphyry and before the deposition of the Cretaceous beds. Their age is therefore early Mesozoic. Their

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[1] RANSOME, F. L.: Geology and Ore Deposits of the Bisbee Quadrangle, Arizona. U. S. Geol. Survey *Prof. Paper* 21, 1904.

RICE, C. T.: Camp of Bisbee, Ariz. Mines and Methods, vol. 1, p. 241, Salt Lake City, Utah, 1909.

DOUGLAS, JAMES, NOTMAN, ARTHUR, LEGRAND, CHARLES, LEE, G. B.: The Copper Queen Mines and Works. Inst. Min. and Met. *Trans.*, vol. 21, pp. 532–590, 1913; *Eng. and Min. Jour.*, Mar. 8, 1913.

RANSOME, F. L.: Notes on the Bisbee District, Arizona. U. S. Geol. Survey *Bull.* 529, pp. 179–182, 1913.

JENNEY, J. B.: Bisbee Porphyry Deposits. *Eng. and Min. Jour.*, vol. 97, p. 467, 1914.

BONILLAS, Y. S., JENNEY, J. B., and FEUCHÈRE, LEON: Geology of the Warren District. Am. Inst. Min. Eng. *Bull.* 117, pp. 1397–1466, 1916.

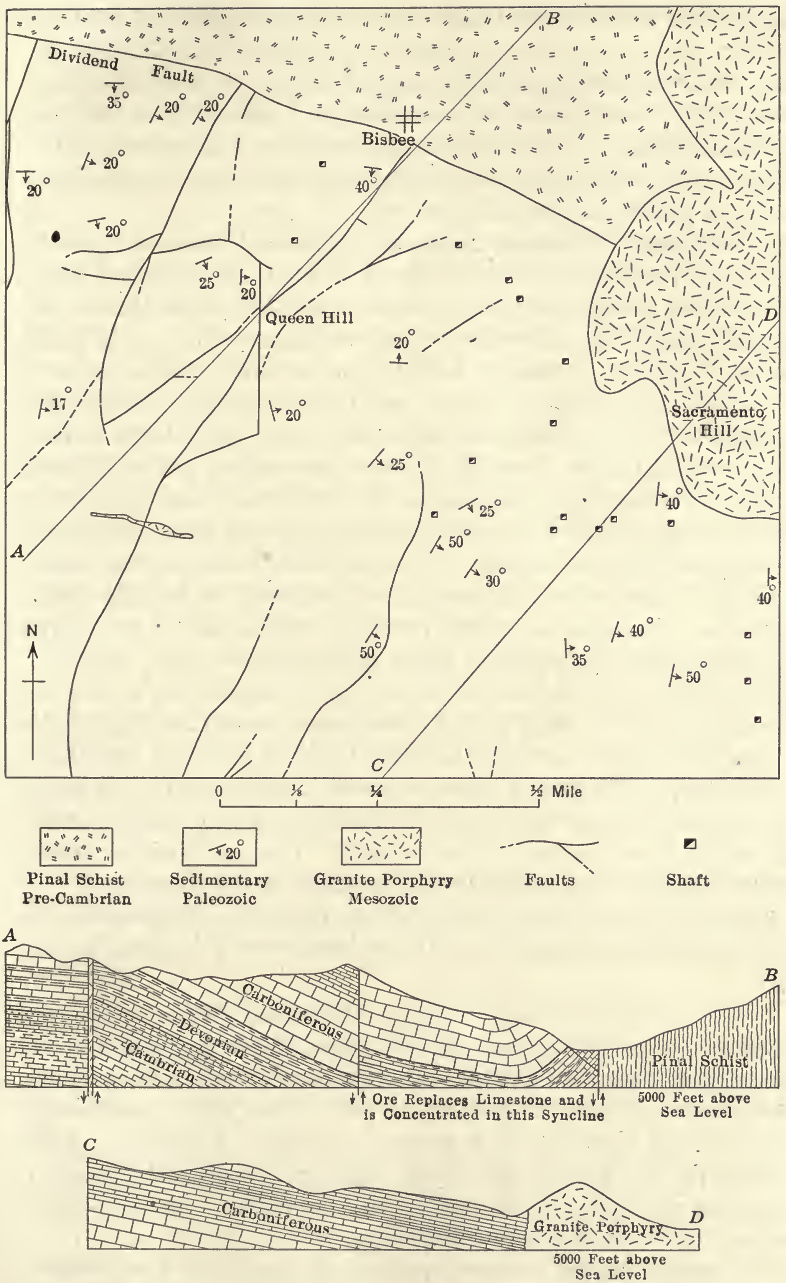

Fig. 158.—Sketch and sections of part of Bisbee district, Arizona. (*Based on map by Ransome, U. S. Geol. Survey.*)

deposition was connected with contact metamorphism of the limestones, shown by the development of tremolite, diopside, garnet, and other silicates, generally in crystals of microscopic size. The ore bodies first worked are those in the Carboniferous and Devonian limestones, but recent developments have discovered lenticular masses of ore in the Cambrian limestone, and disseminated ore has been found in the porphyry.

According to Ransome the larger structural features to which the occurrence of the ores is related are (1) the Dividend fault, which has brought Paleozoic beds on the southwest side of the fissure against Pinal schist on the northeast side; (2) a small stock of granite porphyry intruded on the line of the fault and invading the contiguous schist and Paleozoic beds; (3) an open syncline in the down-faulted Paleozoic beds, which dip in part toward the porphyry stock and in conjunction with the fault plane form a trough pitching to the southeast; and (4) a gentle tilt to the southeast, as shown by the present slope of the pre-Comanche erosion surface. The ore bodies occur in the down-faulted fragment of a syncline, are disposed in roughly semicircular fashion around the porphyry stock, and have radial prolongations along certain zones of fissuring.

Though very irregular in form, the ore masses as a rule are roughly lenticular and tend to conform with the bedding of the limestone. Their average thickness is about 33 feet. The shape and position of many of them, however, are determined by zones of fissuring and by the form of intruded porphyry masses, many of which do not extend to the surface. The principal ore bodies were originally deposited by replacement of the limestones. In many of the ore bodies in the Abrigo limestone the positions of former bedding planes are clearly shown by a banding in the ore.

Up to 1904 nearly all the copper obtained at Bisbee came from oxidized or enriched ore. Of late years, however, primary ores have been worked. The most abundant sulphides in the primary ore are pyrite and chalcopyrite. With these may be associated considerable bornite and, in certain ore bodies, magnetite. Both sphalerite and galena have been found in considerable quantity near the porphyry of Sacramento Hill, but these minerals are not widely distributed in the copper ores.

In general in the northern part of the productive area much enriched sulphide ore lies above the original water level, and in the southern part there is considerable oxidized material below it.

The lower limit of enrichment is irregular and ill defined but, like the lower limit of oxidation, is deeper in the southern part of the productive area than in the northern part. In some places sulphide enrichment has worked down to the bottom of a pyrite ore body; in others it has worked around and under residual masses of unenriched pyritic material; and in parts of the Briggs mine large masses of leached and oxidized material rest directly on unenriched, low-grade pyrite. The enriching mineral is generally chalcocite. In some loose, friable ore the chalcocite occurs as thin shells around grains of pyrite and as a sooty interstitial powder.

The great depths to which oxidation and enrichment have penetrated at Bisbee and the inclined position of these zones of alteration with reference to the present underground water level and their approximate parallelism with the old pre-Comanche erosion surface indicate that much of the oxidation and enrichment were effected before the final tilting and before the deposition of the Cretaceous formations.

Globe and Miami, Ariz.—The Globe district, in Gila County, Arizona, ranks fifth in the United States (1915) in the production of copper. At Miami, 6 miles west of Globe, there are enormous quantities of low-grade chalcocite ores disseminated in schist. The Miami Copper Co. and Inspiration Copper Co., mine a great tonnage of these ores, concentrating them in huge mills.

The region contains pre-Cambrian crystalline rocks, including the Pinal schist and various granitic intrusives, overlain unconformably by Paleozoic beds.[1] The section, after Ransome, is as follows:

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[1] Ransome, F. L.: Geology of the Globe Copper District, Arizona. U. S. Geol. Survey *Prof. Paper* 12, 1903; Geology at Globe, Arizona, *Min. and Sci. Press*, vol. 100, p. 256, 1910; Geology of the Globe District, Arizona, *Idem*, vol. 102, p. 747, 1911.

Tolman, C. F., Jr.: *Min. and Sci. Press*, vol. 99, p. 646, 1909.

Ransome, F. L.: U. S. Geol. Survey *Bull.* 529, pp. 183–186, 1913.

Tovote, W. L.: Globe Mining District, Arizona. *Min. and Sci. Press*, vol. 108, pp. 442–449, 487–492, 1914.

Beckett, P. G.: Water Condition in the Old Dominion Mine. Am. Inst. Min. Eng. *Bull.* 112, pp. 679–710, 1916.

Pre-Mesozoic Stratigraphic Column in the Globe Region, Arizona

	Erosion surface		Feet
8.	Thick-bedded gray limestone (Carboniferous)		1,000
7.	Thin-bedded limestone (Devonian)		325
6.	Quartzite (Cambrian)		400
5.	Cherty, dolomitic limestone (Cambrian)		250
4.	Dripping Spring quartzite	Cambrian or older	450
3.	Barnes conglomerate		10 to 55
2.	Pioneer shale		200
1.	Scanlan conglomerate		1 to 6

These rocks were extensively intruded, probably during the Mesozoic era, by diabase, largely as great irregular sills, and also by certain masses of granite and quartz monzonite, including probably the Schultze granite. All the rocks mentioned above were covered wholly or in part by a thick flow of dacite, probably in early Tertiary time. The rocks are cut by numerous faults, some older and some younger than the dacite. Normal faults greatly predominate.

The copper deposits occur (1) as lodes in schist, quartzite, limestone, and diabase, which, where they pass through or alongside of limestone, as in the Old Dominion mine, may be connected with large replacement bodies in that rock; (2) as disseminated deposits of chalcocitic ore in the Pinal schist near the Schultze granite (Miami and Inspiration mines); (3) as secondary deposits of chrysocolla in dacite tuff or in fissures.

The primary ore of the lodes consists essentially of pyrite and chalcopyrite, with some bornite and specularite. Galena and sphalerite are rather rare. In the disseminated deposits in schist the primary metallic minerals are pyrite and chalcopyrite with a little molybdenite.

The deposition of the disseminated protore in schists was connected with the intrusion of the Schultze granite, the constituents of the sulphides probably emanating from the magma reservoir that supplied that rock. The lode ores were also deposited at high temperature and may likewise be genetically connected with the granitic magma. They are, however, more closely associated with the diabase, and possibly this rock had some share in their genesis.

The ore bodies in limestone of the Old Dominion (Fig. 159) and neighboring mines were large irregular masses of oxides and

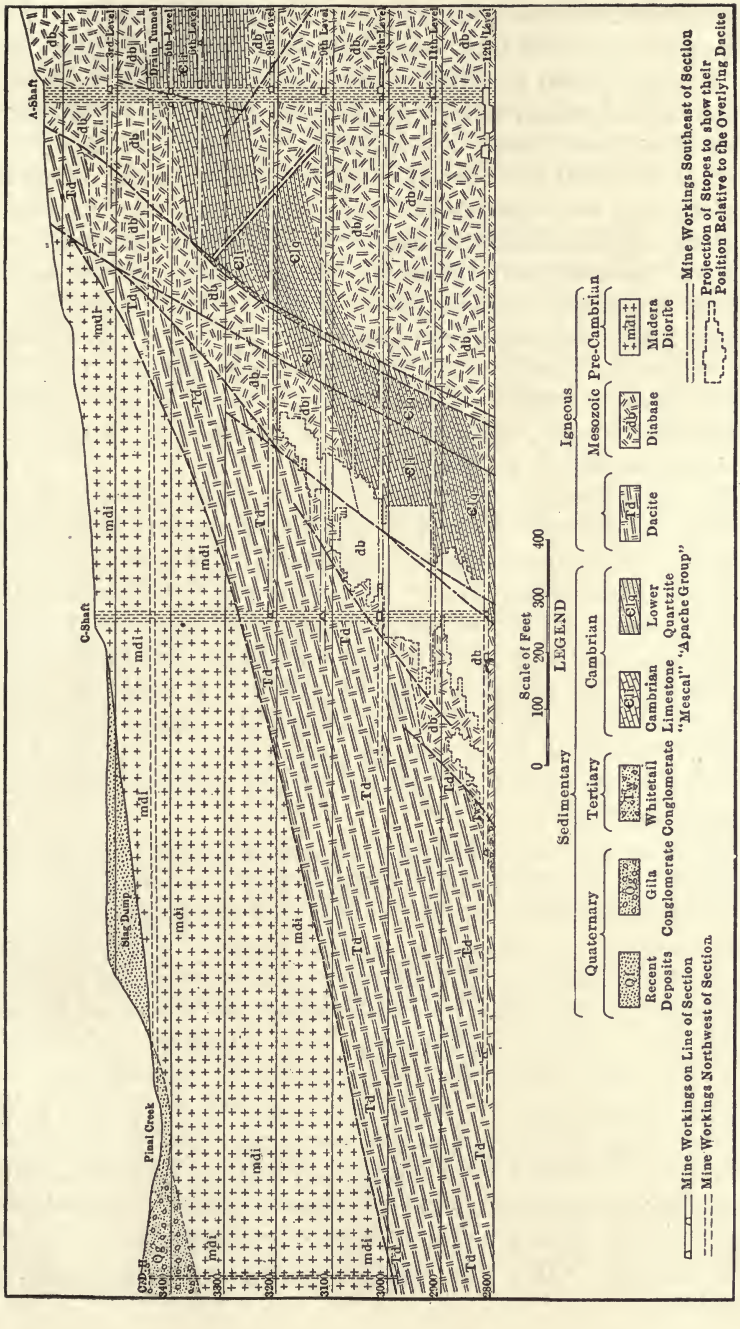

FIG. 159.—Cross-section of Old Dominion mine, Globe, Arizona. (*After Beckett.*)

carbonates associated with much limonite and hematite. In the lodes connected with these masses oxidized ore prevails generally to a depth of 700 to 800 feet but extends much deeper in the much faulted ground under the Gila conglomerate, in the western part of the mine, where it is found on the 1,600-foot or bottom level about 1,200 feet below the surface. It is highly probable that much of the oxidation and enrichment at the Old Dominion lode was effected before the deposition of the Gila conglomerate.

Under the oxidized ore in the Old Dominion and adjacent lodes, mainly in diabase, are large bodies of ore enriched by chalcocite, which grade irregularly downward into pyrite or into pyritic ore containing chalcopyrite, bornite, and specularite. The Old Dominion ore[1] (1911) averaged 5.84 per cent. copper. Silver and gold, though present, are not as abundant as in the ores replacing limestone at Bingham, Utah.

The disseminated deposits in schists near Miami form a chain of large ore bodies extending in a gentle curve from the Miami mine on the east through the Inspiration, Keystone, and Live Oak mines toward the west. The western limit of this ore belt is undetermined. The chain as at present developed is 2 miles long and a quarter of a mile in maximum width, and the greatest thickness of ore along any one vertical line is about 300 feet. Estimates by the engineers of the mines give a total of 80,000,000 to 90,000,000 tons of ore averaging between 2 and 2.5 per cent. of copper. The ore of workable grade will probably amount to 150,000,000 tons.

The secondary ore consists of pyrite and chalcocite in a siliceous gangue. Some gold and silver are present. In milling this ore is concentrated about 20 to 1, with a high extraction of copper. The concentrates carry 40 per cent. of copper. Apparently the chalcocitization of iron sulphides has gone more nearly to completion at Miami than in disseminated ores elsewhere in the Southwest. At Ray and Morenci, Ariz.; Bingham, Utah; and Ely, Nev., the concentrates carry much more iron sulphide.

The country rock of the Miami-Inspiration ore zone is in general Pinal schist, but good ore occurs also in dikes and small offshoots that extend into metallized schist from the main granite mass, which grades into porphyry on its margins. In general the unmetallized Pinal schist is a bright-gray fissile rock, splitting

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[1] Butler, B. S.: U. S. Geol. Survey *Mineral Resources*, 1911, part 1, p. 284, 1912.

with a satiny sheen and showing considerable variations in color, texture, and degree of metamorphism. It is composed of quartz, sericite, a little microcline and plagioclase, magnetite, zircon, tourmaline, hornblende, biotite, and chlorite. As a whole, the schist was derived by metamorphism from arkose sedimentary beds, although it includes a little material of probable igneous origin.

During the primary period of metallization pyrite, chalcopyrite, and quartz were deposited in the fractured schists, partly in fissures an inch or so wide but chiefly in much smaller cracks or along cleavage planes. During the period of enrichment the downward-moving cupriferous solutions replaced the chalcopyrite and pyrite wholly or in part by chalcocite. Enrichment probably antedated the deposition of the Gila conglomerate, according to Ransome, and possibly preceded the eruption of the dacite, and it has probably continued to the present day. Where erosion has overtaken the chalcocite zone enrichment has apparently been checked because little pyrite is available in the thoroughly chalcocitized schist to form strongly acid solutions, and the copper, instead of migrating downward, remains near the surface as chrysocolla and carbonates.

As a whole, the disseminated ore bodies form an irregularly undulating ribbon of very uneven thickness. The distance from the surface of the ground to the top of the ore varies widely from place to place and is not definitely related to the present topography, which apparently is of later development than the main period of enrichment. At the Miami mine the depth of ore is in general between 200 and 400 feet, on the Inspiration ground it ranges from 50 to 600 feet, and on the Live Oak ground it reaches 1,000 feet.

Ray, Ariz.—The Ray (Mineral Creek) district,[1] is near Kelvin, Ariz., and about 20 miles southwest of Globe. It occupies

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[1] Ransome, F. L.: Geology of the Globe District, Arizona. *Min. and Sci. Press.*, vol. 102, p. 747, 1911.

Weed, W. H.: The Ray Copper Mining District, Arizona. *Min. World*, vol. 34, p. 53, 1911.

Tolman, C. F., Jr.: Disseminated Chalcocite Deposits at Ray, Arizona. *Min. and Sci. Press*, vol. 99, p. 622, 1909.

Clifford, J. O.: Ray Consolidated Properties. *Mines and Methods*, vol. 4, p. 83, Salt Lake City, Utah.

Ransome, F. L.: U. S. Geol. Survey *Bull.* 529, p. 186, 1913, *Bull.* 625 pp. 216–217, 1917.

a hilly depression that is drained by Mineral Creek, between the Dripping Spring and Tortilla ranges. In the productive area the altitude ranges from 1,900 to 2,900 feet above sea level, and the low hills are steep and rugged. The production of the district is large, and it is stated that 83,000,000 tons of ore, with an average content of 2.17 per cent. of copper, are developed. The ore is concentrated to a product containing 22 per cent. of copper.

The geologic formations are in general similar to those in the Globe region, the Pinal schist at Ray being intruded by two varieties of granite porphyry, one of which very closely resembles the porphyritic facies of the Schultze granite.

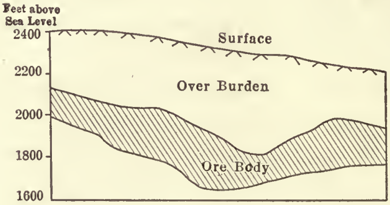

Fig. 160.—Section of part of an ore body at Ray, Arizona. (*After Tolman.*)

The ore bodies are mainly in the schist, although masses of granite porphyry within the generally metallized area have also been converted to ore. The deposits are of the disseminated type; the siliceous, sericitized schist is sheeted, fractured, and filled with innumerable closely spaced veinlets of copper sulphides, which occur also in the schist between the veinlets. The protore is probably connected genetically with the granite porphyry.

The ore bodies underlie a group of hills stained here and there with copper minerals. The principal area showing this alteration is of elongated oval shape and extends west-northwestward from Mineral Creek for about 2½ miles. Within this area there is a continuous ore body about 8,000 feet long and 2,500 feet in greatest width. As at Miami, the layer of ore has many irregular undulations (Fig. 160) that apparently have no relation to the present topography. The average thickness of the ore body is 101 feet; of the overburden 250 feet. The depth to ore ranges from 10 to 300 feet and the thickness of the ore from a thin film to 400 feet.

Morenci, Ariz.—The Morenci district, in eastern Arizona, to the end of 1915, has produced 1,221,296,000 pounds of copper, ranking fourth among the copper districts in the United States. Some of the ore, yielding about 4 per cent. of copper, is smelted directly; a larger amount, yielding about 2 per cent., is concentrated. Only a little gold and silver is present in the ores.

The Morenci district[1] is an area of pre-Cambrian granite and quartzitic schists, above which rest unconformably about 1,500 feet of Paleozoic sandstones, limestones, and shales that are locally overlain unconformably by Cretaceous shales and sandstones (Fig. 161). These rocks are intruded by masses of granitic and dioritic porphyries, which form stocks, dikes, laccoliths, and sheets. All these rocks have been subjected to uplift and warping or doming, succeeded by much faulting during latest Cretaceous or earliest Tertiary time. The domed area of older rocks is framed by great masses of Tertiary basalt and rhyolite, with some andesite. Active erosion has taken place since early Tertiary time, removing the covering of lavas. Some of the material eroded was deposited at the foot of the mountains, forming the Quaternary Gila conglomerate. Still later deep canyons were cut in the conglomerate.

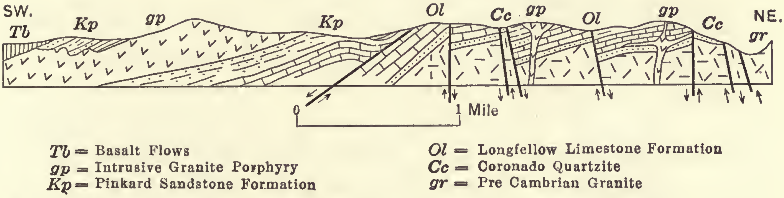

FIG. 161.—Section through Morenci, Arizona. (*After Lindgren, U. S. Geol. Survey.*)

The ore bodies, as stated by Lindgren, are veins and disseminated deposits in the granitic and quartz monzonite porphyry and contact-metamorphic deposits in the limestone and shale near the porphyry. The veins and disseminated deposits are most productive.

The ore deposits are in or near the intruding porphyry and were probably formed by solutions emanating from igneous bodies. The contact-metamorphic deposits have formed in Paleozoic limestone and shale near the porphyry; where the

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[1] LINDGREN, WALDEMAR: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey *Prof. Paper* 43, 1905.

REBER, L. E.: The mineralization at Clifton-Morenci. *Econ. Geol.*, vol. 11, pp. 528–573, 1916.

porphyry cuts granite or quartzite little change is noted. By contact metamorphism pure limestones and calcareous shales were changed to ore consisting of pyrite, chalcopyrite, zinc blende, magnetite, garnet, epidote, diopside, tremolite, and quartz. At many places the ores were formed along certain beds that were evidently more favorable for their development than others. In form these deposits are irregular, but some are rudely tabular, the mineralization having followed certain beds or the walls of dikes. Lindgren considers these deposits contemporaneous with the cooling and solidification of the porphyry.

Oxidation of the contact-metamorphic deposits is not so deep as in the veins in porphyry. Cuprite and copper carbonates constitute extensive and rich ore bodies in the shales and limestones. Magnetite and garnet decompose to limonite and quartz; sphalerite is removed almost completely. By oxidation copper is concentrated; some also is scattered in the country rock.

The veins cut granitic porphyry, and sedimentary rocks. They are composed of pyrite, chalcopyrite, sphalerite, molybdenite, sericite, and quartz. A few, generally of small value, carry also magnetite, tremolite, diopside, and epidote.

The disseminated ores in porphyry are formed by filling small but closely spaced cracks in the porphyry and replacing the rock nearby. Some of these deposits are large, and they constitute the mainstay of the camp.

COPPER PRODUCED IN CLIFTON-MORENCI DISTRICT, ARIZONA, 1913–1915[a]

Year	Quantity, pounds	Average yield of copper from ore, per cent.
1913	70,100,000	2.00
1914	66,000,000	1.95
1915	51,096,000	2.01

[a] BUTLER, B. S.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 682, 1916.

The veins and disseminated deposits owe much of their workable ore to processes of enrichment. Near the surface they are oxidized and generally leached of copper. Not all are marked by heavy gossans, and in the outcrops of some there is but little iron. Below the leached zone is a zone of chalcocite ore in which the copper sulphide replaces pyrite and zinc blende, below the chalcocite ore the primary sulphides are found including pyrite, chalcopyrite and sphalerite.

Ely, Nev.—The Ely (Robinson) district, in White Pine County, eastern Nevada, has long been known as a metallized area but did not begin active production of copper until 1908. The barren capping is removed and the ore is mined by steam shovels and concentrated about 11 to 1. About 10,000 tons of ore are treated daily. The Nevada Consolidated Copper Co. is the principal operator in the district.

METALS PRODUCED BY NEVADA CONSOLIDATED COPPER CO., ELY, NEV., 1912–1915[a]

Year	Ore treated, short tons	Copper, per cent.	Extraction of copper, per cent.	Gold and silver recovered per ton, cents	Copper produced, pounds	Cost of copper per pound, cents
1913	3,139,137	1.599	68.52	12.32	64,972,829	9.99
1914	2,640,294	1.483	68.48	13.45	49,244,056	10.16
1915	3,081,520	1.540	70.18	18.56	62,726,651	8.67

[a] BUTLER, B. S.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 706, 1916.

The Ely district[1] is an area of folded and faulted Paleozoic limestones and shales ranging in age from Silurian to Carboniferous. These formations are intruded by monzonite porphyry along an east-west zone about 9 miles long and from ½ to 1 mile wide. These rocks are locally overlain by rhyolite flows of Tertiary age. The sedimentary rocks near the porphyry intrusions are locally garnetized or changed to jasperoid and commonly charged with great quantities of pyrite. In places near the igneous masses considerable amounts of chalcopyrite occur with the pyrite, and some sphalerite is present. Galena and its oxidation products occur in irregular lodes within the metamorphic area, principally at some distance from the porphyry masses. Gold ores with lead carbonate occur mainly as blanket lodes.

Of many superficial showings of copper carbonates none have been developed profitably, but oxidized ores of relatively high grade have been discovered in the Alpha mine, at considerable

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[1] LAWSON, A. C.: The Copper Deposits of the Robinson Mining District, Nevada. Cal. Univ., Dept. Geology *Bull.*, vol. 4, No. 14, pp. 287–357, 1906.

SPENCER, A. C.: Preliminary Geologic Map of the Vicinity of Ely, Nev. U. S. Geol. Survey, 1912. U. S. Geol. Survey *Bull.* 529, pp. 189–191, 1913; *Bull.* 625, pp. 219–221, 1917.

depth. This ore body is inclosed by metamorphosed and thoroughly oxidized sedimentary rocks that lie several hundred feet from the nearest porphyry.

The principal deposits are low-grade disseminated ores in the porphyry (Fig. 162). As stated by Spencer, the porphyry was locally fractured after its intrusion, and great masses of it were filled with veinlets of quartz, carrying pyrite and chalcopyrite.

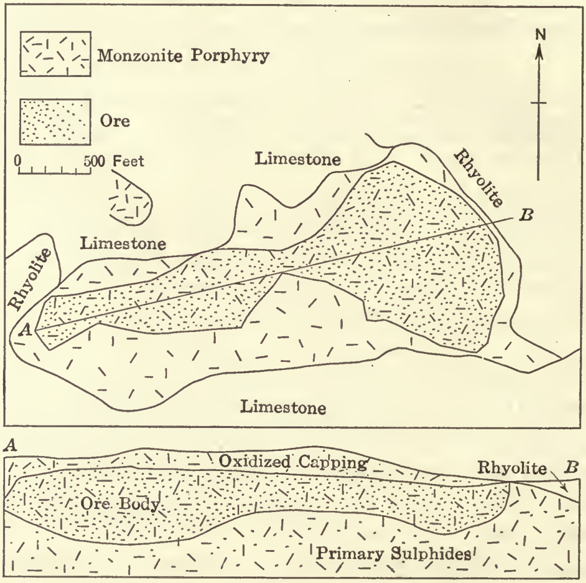

FIG. 162.—Map and cross-section of disseminated deposit in porphyry at Ely, Nevada. (*Based on maps by Nevada Consolidated Copper Co.*)

Near the fractures the porphyry was charged with sulphides by replacement, and the rock was greatly altered, lime, magnesia, soda, and iron being removed and considerable potash being added. These hydrothermal changes involved the destruction of hornblende and lime-soda feldspar and the formation of brown mica and sericite. Some fluorite is present. The outcrops of the ore masses are said to carry not over 0.5 per cent. of copper. There is an abrupt change from this capping to soft blue-white porphyry ore, which carries disseminated sulphide minerals, including copper glance, as films coating grains of pyrite and chalcopyrite, or, less commonly, completely replacing such grains.

The Nevada Consolidated Co.'s ore bodies have a capping that averages 102.5 feet in thickness, below which lies the chalcocite zone, which has an average thickness of 218 feet. This company has developed more than 50,000,000 tons of the disseminated ore averaging 1.7 per cent. of copper. The profitable ore is known to extend locally to depths of about 600 feet. A hole was put down nearly 400 feet below the ore body, in material which carried less than 0.4 per cent. of copper.[1]

A composite analysis of 1,000 samples of ore from the Ruth mine, stated by A. C. Lawson, may be calculated as equivalent to pyrite, 10 per cent.; chalcopyrite, 1.8 per cent.; and chalcocite, 2 per cent. According to Spencer any porphyry in this district carrying more than 1 per cent. of copper probably owes its grade to the presence of chalcocite, the enrichment having resulted from precipitation of this mineral out of solutions derived from overlying material.

Santa Rita, N. Mex.—The Santa Rita district,[2] in Grant County, New Mexico, was known to the Spaniards in the later part of the eighteenth century, when copper was mined and carried to Mexico City. The yield was small, however, until 1911, when the Chino Co. began production on a large scale. The deposits are of the disseminated type, but they differ from the disseminated ores of Morenci, Ely, and Bingham, for a large proportion of the copper is native metal or in cuprite. The ore is mined by steam shovels, concentrated near the mines, and smelted at El Paso, Texas. In the disseminated ores on the Chino ground 90,000,000 tons of ore averaging 1.75 per cent. of copper was developed in 1913. Most of it is near the surface. The average thickness of the capping is 82 feet, and the average thickness of the ore below the capping is 107 feet.

The country (Fig. 163) comprises an area of Paleozoic quartzites and limestones, unconformably above which lie Cretaceous quartzites and schists. Above the Cretaceous rocks, also unconformably, are Tertiary lavas and tuffs. The Cretaceous

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[1] Nevada Consolidated Copper Co., *Fifth Ann. Rept.*, for 15 months ended Dec. 31, 1911, p. 8.

[2] PAIGE, SIDNEY: The Geologic and Structural Relations of Santa Rita (Chino), N. Mex. *Econ. Geol.*, vol. 7, p. 547, 1913; U. S. Geol. Survey *Geol. Atlas*, Silver City folio (No. 199), 1916.

LINDGREN, WALDEMAR, GRATON, L. C., and GORDON, C. H.: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68, p. 305, 1910.

and older rocks are intruded by diorite and associated igneous rocks, by quartz diorite porphyry, and by quartz monzonite and quartz monzonite porphyry. Subsequently, in Tertiary time, the rhyolite flows and intrusions and basalt flows were formed. Folding attended the intrusions of diorite, and faulting followed the extravasation of Tertiary lavas. Finally, Quaternary sediments with interbedded basalts were deposited. Zones of garnet are extensively developed in limestone and, according to Paige, the quartz monzonite porphyry has greatly metamorphosed the quartz diorite porphyry intrusives by the development of sericite, epidote, and quartz and the recrystallization of the iron in the dark silicates to form sulphides. The quartz monzonite porphyry carries most of the disseminated ore. It is highly sericitized and contains sulphides and secondary silica. By oxidation iron oxides and kaolin have been formed. The primary mineralization followed the deposition of the Cretaceous quartzite and preceded the extrusion of the Tertiary lavas. According to Paige the country was peneplained after the ore

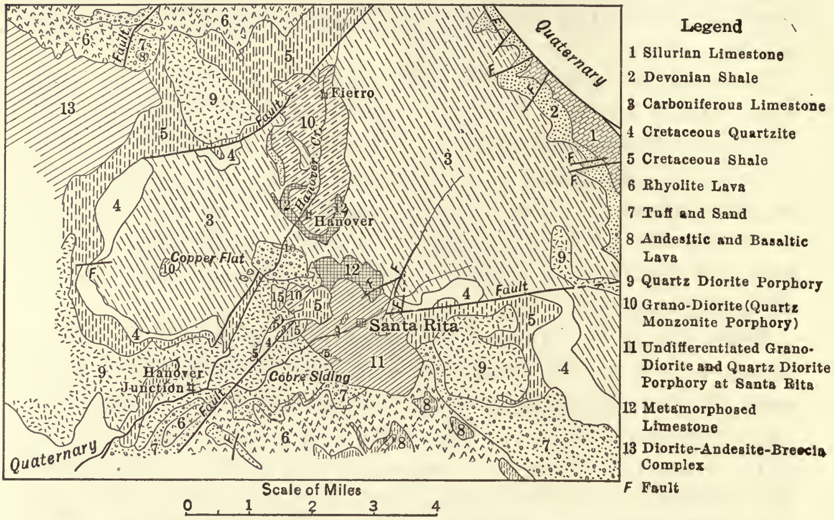

FIG. 163.—Map of Santa Rita district, New Mexico. 1, Silurian limestone; 2, Devonian shale; 3, Carboniferous limestone; 4, Cretaceous quartzite 5, cretaceous shale; 6, rhyolite lava; 7, tuff and sand; 8, andesitic and basaltic lava; 9, quartz diorite porphyry; 10, granodiorite (quartz monzonite porphyry; 11, undifferentiated granodiorite and quartz diorite porphyry at Santa Rita; 12, metamorphosed limestone; 13, diorite andesite breccia complex; *F*, fault. (*After Paige.*)

was deposited, before Tertiary time, and probably enrichment was then well advanced.

At Santa Rita most of the copper occurs as native metal, oxide, or sulphide in altered porphyry. Chalcocite with kernels of pyrite is disseminated both in the quartzite and in the porphyry, and much of the chalcocite has doubtless replaced pyrite. Outside the bodies of copper ore pyrite is distributed similarly to the chalcocite within the ore bodies. Primary sulphides have altered to chalcocite and chalcocite to oxide and native copper.

METALS PRODUCED BY CHINO COPPER CO., 1913–1915[a]

Year	Ore milled, short tons	Copper content, per cent.	Mill recovery, per cent.	Production of refined copper, pounds	Cost of copper per pound, cents
1913	1,942,700	2.033	67.310	50,511,661	8.77
1914	1,907,300	2.115	67.858	53,999,928	7.60
1915	2,379,800	2.155	66,588	64,887,788	7.12

[a] BUTLER, B. S.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 103, 1916.

Burro Mountain District, N. Mex.—The Burro Mountain region,[1] in Grant County, New Mexico, is arid and stands 5,000 to 8,000 feet above sea level. The main mass of the mountains consists of pre-Cambrian granite and pegmatite and dioritic rock, which is locally gneissic. These rocks are intruded by quartz porphyry and quartz monzonite porphyry. Remnants of volcanic breccia cap the older intrusive rocks.

The monzonite porphyry and quartz porphyry are locally fractured and are traversed by innumerable small joints and fissures. The fracture zone in the principal mineralized area is believed by Somers to have been formed by stresses that attended the extrusion of lavas; that it is not caused by contraction of the

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[1] LINDGREN, WALDEMAR, GRATON, L. C., and GORDON, C. H.: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68, pp. 322–323, 1910.

LANG, S. S.: The Burro Mountain Copper District. *Eng. and Min. Jour.*, vol. 82, p. 395, 1906.

PAIGE, SIDNEY: Metalliferous Ore Deposits near the Burro Mountains, Grant County, New Mexico. U. S. Geol. Survey *Bull.* 470, p. 131, 1910.

SOMERS, R. E.: The Burro Mountain Copper District. Am. Inst. Min. Eng. *Bull.* 101, pp. 957–996, 1915.

monzonite on cooling is evident, for only a small part of the monzonite mass is fractured. In these fractures and in the wall rock between them much quartz, pyrite, chalcopyrite, and sphalerite have been deposited. Sericite and quartz have been developed in the wall rock by hydrothermal metamorphism, particularly near the veins. The ore near the surface is leached of the sulphides; limonite, hematite, chalcedony, and kaolin mark the outcrops. With these minerals in the oxidized zone are associated some malachite, azurite, and chrysocolla and small quantities of cuprite and native copper. Below the surface a zone of chalcocite having a maximum thickness of 200 to 300 feet is developed over most of the mineralized area. The rock in this zone carries about 2 or 3 per cent. of copper. In it chalcocite has replaced pyrite, chalcopyrite, and sphalerite. Below the chalcocite zone is low-grade material carrying pyrite and finely divided chalcopyrite and sphalerite.

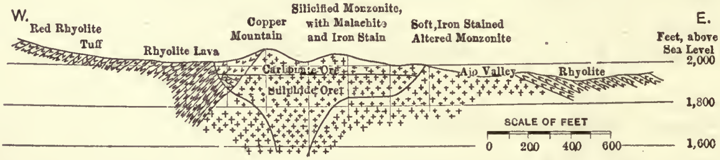

FIG. 164.—Vertical section through New Cornelia ore body, Ajo, Arizona. (*After Joralemon.*)

Ajo, Ariz.—The Ajo district,[1] in south-central Arizona, contains disseminated copper ores in porphyry, in which oxidation appears to have been attended by little leaching and chalcocitization. The most notable feature of this region is an intrusive mass of monzonite porphyry, which has domed up the older rhyolite beds (Fig. 164).

Some rich copper veins occur in the porphyry and in the rhyolite, but the most valuable deposits developed are in a mass of shattered porphyry that occupies about 55 acres and has a maximum depth of 600 feet, carrying about 12,000,000 tons of carbonate ore, below which lies about 28,000,000 tons of sulphide ore. Unlike the disseminated deposits at Bingham and Ely, in which the copper ore is largely chalcocite, the disseminated ores in the Ajo district are chalcopyrite and bornite. The porphyry is

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[1] JORALEMON, I. B.: The Ajo Copper-Mining District. Am. Inst. Min. Eng. *Trans.*, vol. 49, p. 593, 1915.

highly shattered. Along some of the larger fractures the seams of bornite and chalcopyrite widen to veins an inch or more across. Where several of these veins are parallel and closely spaced there are bands of ore, 10 to 100 feet wide, assaying from 3 to 5 per cent. of copper. The grade of the ore in general is variable, changing abruptly from porphyry containing less than 0.5 per cent. of copper to ore assaying over 3 per cent. There are excellent examples of the replacement of bornite by chalcocite.[1]

The outcrop and oxidized zone consist of silicified monzonite porphyry, with seams and stains of malachite, limonite, hematite, and a little chrysocolla. The feldspar is partly kaolinized. About 85 per cent. of the copper in the oxidized zone is said to be malachite. Here and there disseminated chalcopyrite and bornite remain unaltered in hard ore between fractures, but such remnants of sulphides are insignificant compared with the great mass of carbonate ore. The oxidized ore extends downward to an almost horizontal plane about 20 feet below the deepest arroyos and 150 feet below the highest hills. This plane is approximately the present ground-water level, and the transition from carbonate to sulphide ore is very abrupt.

Jerome, Ariz.—The Jerome district[2] is in Yavapai County, east-central Arizona, in a group of moderately low and arid hills. Although several mines are being explored, only two, the United Verde and United Verde Extension, have produced much ore. The United Verde mine was once worked for gold but since 1888 has been a steady producer of copper, giving the district the fifth rank in the United States. In 1915 the Jerome district produced 53,260,000 pounds of copper. Recent developments promise an increased production.

The United Verde mine is in an area of pre-Cambrian schists, probably faulted upward, and on the hillside west of the mine the schist is overlain unconformably by Cambrian, Devonian,

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[1] Graton, L. C., and Murdoch, Joseph: The Sulphide Ores of Copper. Am. Inst. Min. Eng. *Trans.*, vol. 45, p. 78, 1914.

[2] Graton, L. C.: U. S. Geol. Survey *Mineral Resources*, 1907, part 1, p. 597, 1908.

Ransome, F. L.: U. S. Geol. Survey *Bull.* 529, p. 192, 1913; *Bull.* 625, pp. 232–233, 1917.

Tupper, C. A.: Mine and Smelter of the United Verde Copper Co. *Min. World*, vol. 42, pp. 717–727, 1915.

and Carboniferous beds. In the vicinity of the mine, as described by Ransome, the schist stands nearly vertical, with rough irregular cleavage, and strikes a little west of north. There are three varieties—(1) a green rock, schistose on its margins but grading into massive material, which is evidently an altered dioritic intrusive; (2) a rough gray schist containing abundant phenocrysts of quartz, apparently an altered rhyolite; and (3) a satiny greenish-gray, very fissile sericitic schist that may be a metamorphosed sediment. The ore occurs in the gray schist and in the sericitic schist, the main belt of dioritic rock lying just west of the ore bodies. The ore is said to follow as a rule the layers of fine sericitic schist.

The ore shoot is oval in plan, about 1,300 feet long horizontally and 700 feet wide. It trends north-northwest and pitches in that direction 45°. It has been worked to a vertical depth of 1,200 feet. The great shoot is in reality a complex of smaller but nevertheless large irregular or lenticular ore bodies, apparently related in part to cross fissuring but showing a tendency toward parallelism with the schistosity.

The ore was deposited in pre-Cambrian time. The chief mineral is chalcopyrite, associated with which are pyrite and sphalerite. The sulphides occur partly in small irregular fractures and along planes of schistosity, but to a large extent they have metasomatically replaced the schist, particularly the fine-grained variety. The ore contains very little vein quartz or other gangue mineral.

Oxidized ore containing malachite, azurite, and cuprite extended to a depth of about 400 feet and in its upper part was comparatively rich in gold. Below the level of complete oxidation there was chalcocite ore with a relatively high proportion of silver. Recently large bodies of rich chalcocite ore inclosed in schist have been discovered below the flat-lying Cambrian sedimentary rocks in the United Verde Extension mine.

Shasta County, Calif.—The copper-bearing region of Shasta County, California,[1] is in the Klamath Mountains, near the

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[1] Diller, J. S.: U. S. Geol. Survey *Geol. Atlas*, Redding folio (No. 138), 1906.

Graton, L. C.: The Occurrence of Copper in Shasta County, California. U. S. Geol. Survey *Bull.* 430, pp. 71–111, 1910.

Boyle, A. C., Jr.: The Geology and Ore Deposits of the Bully Hill Mining District, California. Am. Inst. Min. Eng. *Trans.*, vol. 48, pp. 67–115, 1915.

Hershey, O. H.: The Geology of Iron Mountain. *Min. and Sci. Press*, Oct. 23, 1915, pp. 633–638.

head of Sacramento River, a few miles north of Redding. The ores yield about 3 per cent. of copper and $1.50 to $2 a ton in precious metals. In 1915 Shasta County produced 30,500,000 pounds of copper.

It is an area of sedimentary rocks complexly intruded by several varieties of consanguineous igneous rocks. The oldest sedimentary series comprises the Kennett formation (Middle Devonian), which consists chiefly of black fissile shale, with scattered lenses of light-gray limestone and numerous gray or yellowish beds of tuffaceous material. Overlying the Kennett formation unconformably is the Bragdon formation (Mississippian), which consists chiefly of black and gray shales, with thin interbedded layers of tuff and sandstone and bands of conglomerate. Above the Bragdon is the Pit shale, of Middle and Upper Triassic age, consisting chiefly of shales with interbedded layers of volcanic tuff.

The oldest igneous rock is an altered andesite called by Diller the meta-andesite, which underlies and is older than the Kennett and Bragdon formations. A massive, less altered andesite (Dekkas andesite) overlies the Bragdon and underlies and grades into the Pit. Younger than all these rocks and cutting the latest of them, the Pit shale, are intrusives of soda-rich alaskite porphyry, or soda granite. The alaskite porphyry is cut by quartz diorite, which in turn is cut by acidic and basic dikes that are genetically very closely related to the alaskite porphyry and to the pegmatites of the region. These pegmatites, according to Graton, in places pass over into siliceous masses that are virtually quartz veins and carry sulphides. There are two centers of alaskite porphyry, and each is a center of ore deposition.

The valuable copper deposits consist of large masses of pyritic ore, surrounded in most places by alaskite porphyry but here and there extending into shale. The ores are in part replacement deposits in crushed and shattered zones of alaskite porphyry, which is highly altered by sericitization (soda sericite). The ore bodies are rudely tabular. The Bully Hill deposits, in the eastern district, are steeply pitching. The Shasta King and Balaklala, in the western district, are large flat-lying "lenses." Some of the deposits are over 1,200 feet long and 300 feet wide (Fig. 165).

The deposits are mineralogically simple. Pyrite is the most abundant mineral, and chalcopyrite is the chief copper mineral. Sphalerite is present in varying amount. Some galena is associated with the zinc sulphide, especially in the eastern districts. The gangue minerals are gypsum, calcite, and barite. The minerals that have resulted from the alteration of the primary ore minerals include limonite, magnetite, wad; secondary chalcopyrite, bornite, and chalcocite; cuprite; native copper; small amounts of malachite and azurite; and several sulphates. The ores are believed to have been deposited by hot waters originating in alaskite porphyry. Graton[1] estimates the depth at which the ores were deposited at 5,000 to 6,000 feet and classes them with veins of the middle zone.

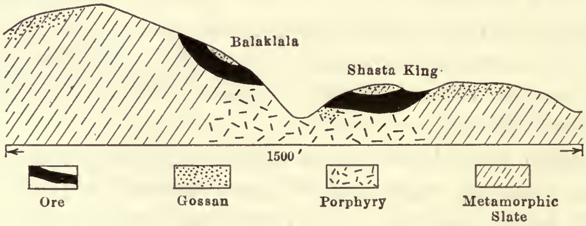

FIG. 165.—Cross-section of ore bodies at Balaklala, Shasta County, California. (*After Weed.*)

The secondary zone was highly productive of copper and silver at the Iron Mountain and Bully Hill mines, but at other mines it is of little economic importance. The secondary ores appear to have extended to no great depth.

Foothill Copper Belt, Calif.—The "foothill belt" in California lies along the foothills of the Sierra Nevada, extending northwestward from Copperopolis to a point near Marysville, a distance of more than 100 miles. It includes the deposits of Copperopolis, Campo Seco, and Dairy Farm. The deposits were worked actively in the sixties and again in recent years. The production to and including 1915 is about 129,400,000 pounds of copper.[2] The principal ores are heavy sulphides, pyrite and chalcopyrite. Those treated in 1915 averaged 5.4 per cent. of copper, with about $1.88 in precious metals to the ton. Sulphuric acid is made from the sulphur gases.

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[1] GRATON, L. C.: *Op., cit.* p. 110.

[2] BUTLER, B. S.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 692, 1916.

The rocks of this area[1] include the "Bedrock series," mainly meta-andesites, greenstones, slates, tuffs and intrusives, metamorphosed in varying degrees. These rocks are cut by hornblendite, gabbro, granodiorite, serpentine, etc. The deposits are related genetically to basic igneous rocks that are older than granodiorite, dikes of which cut the copper ores. At Copperopolis, according to Reid, the ore occurs in overlapping lenses, each of which is composed of pyrite and chalcopyrite, or as a complex series of veinlets of these minerals, or as bands of them parallel to the schists. Only a little quartz is present and a little ilmenite and sphene, which are probably alteration products of a titaniferous pyroxene. Reid states that the ores are related genetically to the small dikes of hornblendite, which are numerous and which were found to carry original chalcopyrite. Some others, however, maintain that they have been formed through concentration of copper from surrounding rocks during the dynamic metamorphism that made amphibolites of basic rocks.

At Copperopolis the ore is capped by an extensive gossan, locally rich, 30 feet or less thick. There is no zone of sulphide enrichment, a fact which Reid attributed to impermeability of the ores. In depth the heavy sulphides come in, either nearly pure or with a varying proportion of schist. The hypothesis that these ores were deposited before the period of dynamic metamorphism has not been directly stated, although Reid attributes their impermeability to intense lateral pressure.

Encampment, Wyo.—The Encampment district,[2] in southern Wyoming near the Colorado line, has produced over 20,000,000 pounds of copper, with some gold and silver. The country is an area of pre-Cambrian metamorphosed igneous and sedimentary rocks, which are cut by pre-Cambrian gabbro, granite, and quartz diorite. The principal mines are the Doane and the

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[1] Reid, J. A.: The Ore Deposits of Copperopolis, Calaveras County California. *Econ. Geol.*, vol. 2, pp. 380–417, 1907.

Knopf, Adolph: Notes on the Foothill Copper Belt of the Sierra Nevada Cal. Univ. Dept. Geol. *Bull.*, vol. 4, No. 17, pp. 411–421, 1906.

Long, Herbert: The Copper Belt of California. *Eng. and Min. Jour.*. vol. 84, p. 909, 1907.

Turner, H. W.: U. S. Geol. Survey *Geol. Atlas*, Jackson folio (No. 11), 1894.

[2] Spencer, A. C.: The Copper Deposits of the Encampment District, Wyoming. U. S. Geol. Survey, *Prof. Paper*, 25, 1904.

Ferris-Haggarty (Fig. 166), both of them in fractured quartzite. The primary copper ores are chalcopyrite and pyrrhotite. The secondary ores include azurite, malachite, chrysocolla, bornite, chalcocite, and covellite.

The country is about 10,000 feet above the sea; the climate is moist, and ground water is near the surface. The chalcocite zone is shallow, well defined, and carries a high content of precious metals.

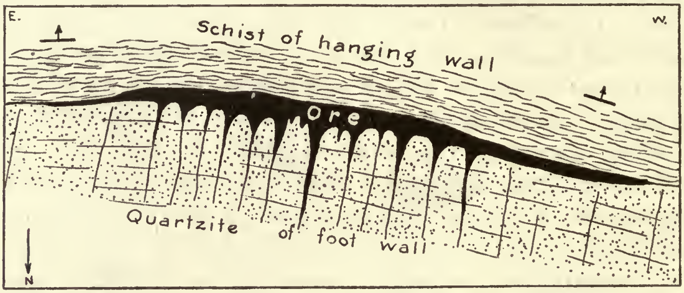

Fig. 166.—Horizontal section of Ferris-Haggarty mine, Encampment district, Wyoming. (*After Spencer, U. S. Geol. Survey.*)

Ducktown, Tenn.—The mineral deposits of Ducktown are in the southeast corner of Tennessee, near the North Carolina line, and extend southward into Georgia. They were first worked in the late forties. Besides large amounts of copper they have produced 1,500,000 tons of iron ore and a relatively small amount of silver and gold. They yield at present, in addition to the metals, over 1,000 tons of sulphuric acid daily. The ore now worked carries less than 2 per cent. of copper. It is heavy iron sulphide ore, principally pyrrhotite, pyrite, and chalcopyrite,

Metals Produced in Ducktown District, Tenn., 1912–1915[a]

Year	Ore treated, short tons	Copper produced, pounds	Average yield of copper, per cent.	Gold and silver per ton of ore, cents
1912	603,229	18,395,256	1.530	10.5
1913	652,253	19,489,654	1.476	11.2
1914	653,621	18,661,112	1.435	9.0
1915	623,534	18,205,308	1.450	

[a] Butler, B. S.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 708, 1916.

with heavy silicates. It is smelted without mechanical concentration. The first smelting yields a 12 per cent. copper matte, which is smelted again to a high-grade matte carrying about 50 per cent. of copper. This is blown to blister copper in Bessemer converters, or shipped without converting. The furnace gases are led to two great acid plants, one of them the largest in the world.

The prevailing rocks of the district[1] are sandy schists and graywackes, with which are interbedded mica schists. The dominant series is the metamorphosed product of Cambrian sedimentary beds, including conglomerate, grits, sandstones, and shales. The beds grade into one another along the strike and across the bedding. They contain small bodies of pegmatites and peculiar masses and stringers of an actinolite-feldspar rock which has a composition near that of quartz diorite. These are supposed to have been developed by metamorphism from material of sedimentary origin. The schists are cut by dikes of gabbro, which are not so highly metamorphosed by pressure as the sedimentary beds. The schistosity and the bedding of the sedimentary rocks strike nearly everywhere northeast, and the prevailing dip is southeast. These rocks have been folded into sharp folds, many of them isoclines. Many of the folds were broken along the crests of anticlines and pass into strike faults that nearly everywhere dip southeast.

The ore bodies[2] (Fig. 167) are replacements of limestone lenses which without much doubt were originally deposited at a single stratigraphic horizon. Anticlines and faulted anticlines, which

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[1] KEITH, ARTHUR: U. S. Geol. Survey, *Geol. Atlas*, Nantahala folio (No. 143), 1907.

[2] SAFFORD, J. M.: "Geology of Tennessee," pp. 469–482, Nashville, 1869.

WHITNEY, J. D.: Remarks on * * * the East Tennessee Copper Mines. *Am. Jour. Sci.*, 2d ser., vol. 20, pp. 53–57, 1855.

ANSTED, D. T.: On the Copper Lodes of Ducktown, in East Tennessee. Geol. Soc. *Quart. Jour.*, vol. 13, pp. 245–254, 1857.

HEINRICH, CARL: The Ducktown Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 25, p. 173, 1896.

KEMP, J. F.: The Deposits of Copper Ores at Ducktown, Tennessee. Am. Inst. Min. Eng. *Trans.*, vol. 31, pp. 244–265, 1902.

WEED, W. H.: Types of Copper Deposits in the Southern United States. Am. Inst. Min. Eng. *Trans.*, vol. 30, p. 480, 1901.

EMMONS, W. H., and LANEY, F. B.: Preliminary Report on the Mineral Deposits of Ducktown, Tenn. U. S. Geol. Survey *Bull.* 470, pp. 151–172, 1911.

are characteristic of this region, are shown also in the ore zone. The ores themselves are somewhat metamorphosed by dynamic processes, and the gangue minerals are bent, but at most places they do not exhibit a well-defined schistosity. They were deposited after the rocks that now inclose them and after the limestone they replace had been subjected to considerable dynamic metamorphism. The outcrops are composed of iron oxides and quartz and contrast strongly with the country rock.

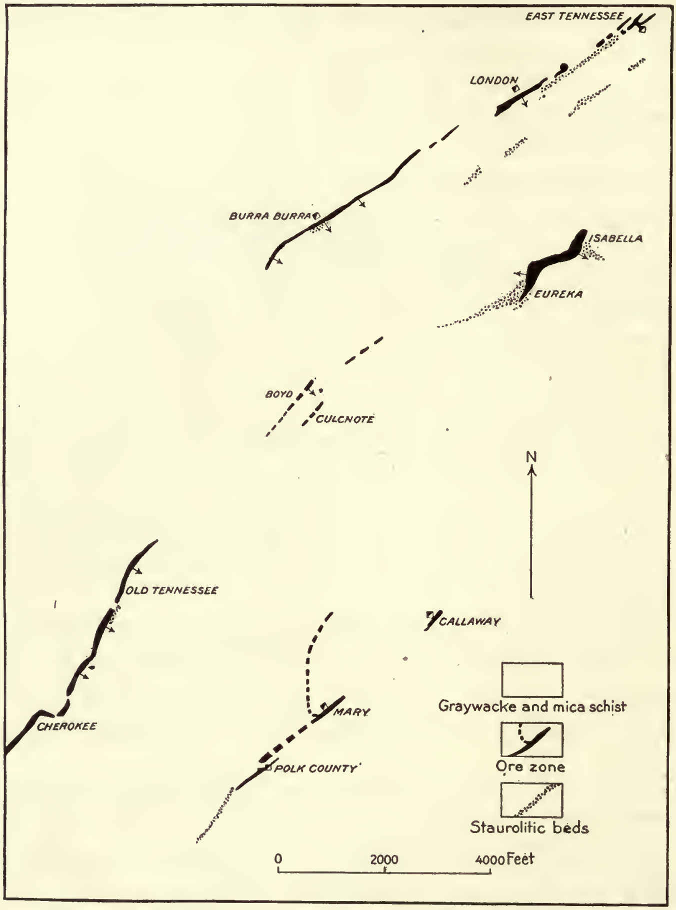

Fig. 167.—Sketch showing location of principal ore deposits in Ducktown district. Tennessee. Arrows indicate dips of lodes.

The primary ore consists of pyrrhotite, pyrite, chalcopyrite, zinc blende, bornite, specularite, magnetite, actinolite, calcite, tremolite, quartz, pyroxene, garnet, zoisite, chlorite, micas, graphite, titanite, and feldspars. Essentially the same minerals are found in all the deposits, but they appear in varying proportions at different places in the lodes. Where its content of copper is above 1.5 per cent., or where its sulphur content is high, the material is ore, but where the proportion of actinolite and other lime silicates is greater and the sulphides are less abundant the material, though containing copper and other sulphides, is not workable.

The association of primary minerals is one that is commonly developed by contact-metamorphic processes or in the deep-vein zone. The deposits are not in contact with igneous rocks but are near intruding gabbro, and a few miles away granites are intruded in rocks as late as the ore-bearing series. The heavy silicates of the gangue are in part contemporaneous with the sulphides, but in much of the ore pyrrhotite and chalcopyrite fill cracks in the silicates.

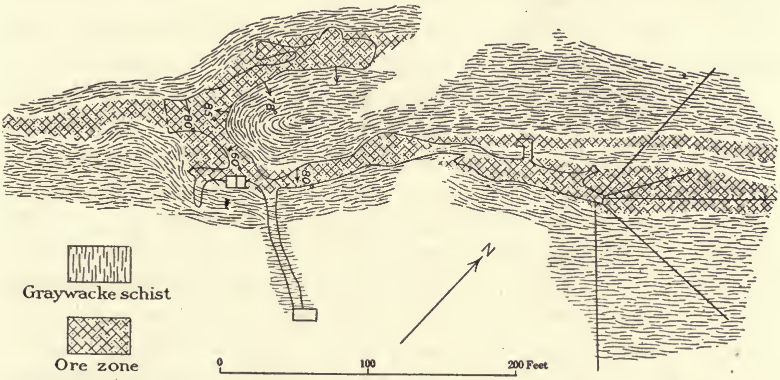

FIG. 168.—Plan of 20-fathom level, East Tennessee mine, Ducktown, Tennessee.

Characteristic structure is shown by Fig. 168. It has resulted from the folding of a limestone bed that was later replaced by ore. The replacing solutions, probably originating in a deep-seated magma, deposited sulphides only sparingly in the inclosing schists but replaced the limestones almost completely.

The gossan extends from the surface to a maximum depth of 100 feet. It carries 40 to 50 per cent. of iron, generally less than 12 per cent. of silica and alumina, and 0.3 to 0.7 per cent. of copper. The minerals are hydrous iron oxides, quartz, jasper, and kaolin, with a little cuprite, native copper, and sulphur. Below the gossan iron ores is a zone of rich copper ores, consisting of chalcocite and other copper minerals in a gangue of sulphates, quartz, and decomposed silicates. Under the higher portions of the outcrops of the lodes the top of this zone is about 100 feet below the surface, but the depth decreases down the slopes, and where the lodes are crossed by running streams the secondary copper ores are exposed at the surface. The upper limit of the chalcocite zone follows the level of ground water, which in turn follows the contour of the country but is less accentuated (Fig. 73, page 164).

The secondary minerals include chalcanthite, chalcocite, chalcopyrite, cuprite, gypsum, and iron sulphate, The copper content of much of this ore ranges from 20 to 30 per cent. An analysis of the gossan and primary ore is given on page 165.

Chitina Copper Belt, Alaska.—The Chitina copper belt, Alaska,[1] is an area of greenstone, mainly diabase, which is overlain by Triassic limestones. Above the limestones are later sedimentary rocks; all these rocks are cut by quartz diorite porphyry. Andesite and other volcanic rocks, probably of Tertiary age, are also present. The country is rugged, and the region of the deposits has been deeply eroded. The principal deposit is a rudely tabular mass of nearly pure chalcocite, which occurs in a fractured or fissured zone in the limestone just above the contact with greenstone. The very rich ore can be traced on the surface for about 250 feet. The deposit carries more than 60 per cent. of copper and 22 ounces of silver to the ton and in 1908 was estimated to contain 100,000,000 pounds of copper.[2] More recently other very large reserves have been discovered in this region by the Kennicott Mining Co.

In the Bonanza mine the very rich ore, with its included limestone, as seen at the surface, has a width of approximately 25 feet, although the thickness of ore sufficiently rich to be mined may be greater. Below the deposit a little chalcocite and bornite are found in some of the shearing planes in the greenstone.

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[1] Moffit, F. H., and Maddren, A. G.: Mineral Resources of the Kotsina-Chitina Region, Alaska. U. S. Geol. Survey *Bull.* 374, p. 80, 1909.

Moffit, F. H., and Capps, S. R.: Geology and Mineral Resources of the Nizina District, Alaska. U. S. Geol. Survey *Bull.* 448, 1911.

[2] Graton, L. C.: U. S. Geol. Survey *Mineral Resources*, 1907, part 1, p. 592, 1908.

Though it extends to the very surface and accumulates in talus from the cliff, the chalcocite ore has no great vertical range. Owing to the rapid mechanical disintegration and the cold climate little or no gossan is developed. Open cavities in the fractured limestone have been filled with ice, and both the country rock and the talus are frozen all summer except for a few feet at the surface. Tolman[1] has shown that in the Bonanza mine chalcocite replaces bornite.

Lake Superior Copper Deposits.—The Lake Superior copper deposits are in the Keweenawan, the upper series of the Algonkian of the Lake Superior region. The Keweenawan series consists of interbedded lava flows, sandstones, and conglomerates, intruded by acidic and basic porphyries. The bedded series is perhaps 25,000 feet or more thick. It borders the larger part of the west half of Lake Superior and extends southwestward through Wisconsin to Taylors Falls and Pine City, Minn., and beyond. On Keweenaw Point, Mich. (Fig. 169), the series dips northwest; on Isle Royale and on the north shore of Lake Superior it dips southeast. Thus the Keweenawan rocks form a broad geosyncline, the axis of which is in Lake Superior (see Fig. 132, page 298). The section for Keweenaw Point,[2] as described by Irving, is stated below.

12. Eastern sandstone.

Keweenawan series:

11. Red sandstone.
10. Black shale and gray sandstone ("Nonesuch belt").
9. Red sandstone and conglomerate ("Outer conglomerate").
8. Diabase and diabase amygdaloid, including at least one conglomerate belt ("Lake Shore trap").
7. Red sandstone and conglomerate ("Great conglomerate").
6. Diabase and diabase amygdaloid, including several sandstone belts.

[1] Tolman, C. F.: Observations on Certain Types of Chalcocite and Their Characteristic Etch Patterns. Am. Inst. Min. Eng. *Bull.* 110, pp. 401–408, 1916.

[2] Irving, R. D.: The Copper-Bearing Rocks of Lake Superior. U. S. Geol. Survey *Mon.* 5, pl. 17, 1883.

Wright, F. E.: The Intrusive Rocks of Mount Bohemia, Michigan. Mich. Geol. Survey *Ann. Rept.* for 1908, pp. 361–402, 1909.

Lane, A. C.: Geology of Keweenaw Point. Lake Superior Min. Inst., *Proc.*, vol. 12, p. 93, 1907.

Rickard, T. A.: "The Copper Mines of the Lake Superior Region," New York, 1905.

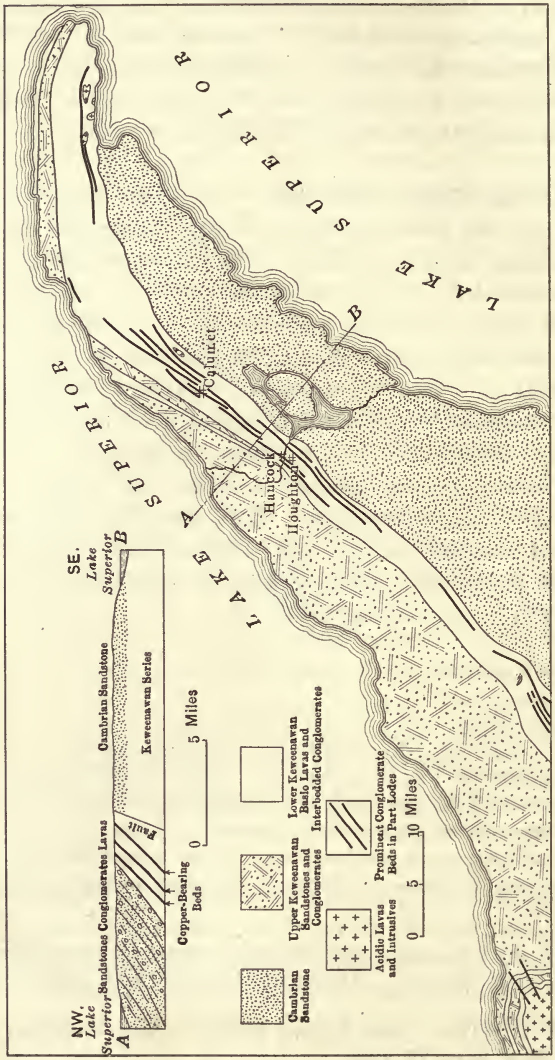

FIG. 169.—Sketch map and cross-section of the Keweenaw copper district, Michigan. (*Based on map by Seaman, and section by Lane.*)

5. Diabase and diabase amygdaloid, including conglomerates.
4. Luster-mottled melaphyres and coarse-grained gabbros and diabases ("Greenstone group").
3. Diabase, diabase amygdaloid, and luster-mottled melaphyre, including a number of conglomerate beds.
2. Quartz porphyry and felsite.
1. Diabase, diabase amygdaloid, melaphyre, diabase porphyry, and orthoclase gabbro, including also conglomerate beds and beds or areas of quartz porphyry and granite porphyry ("Bohemian Range group").

These rocks have a general dip to the northwest and are intruded by gabbro, orthoclase gabbro, and acidic rocks. A fault strikes northeast along Keweenaw Point near its center.

COPPER ORE PRODUCED IN LAKE SUPERIOR DISTRICT, MICHIGAN, 1912–1915[a]

Year	Quantity, short tons	Yield of copper, per cent.
1912	11,411,941	0.96
1913	7,016,370	0.97
1914	9,269,413	0.89
1915	12,334,700	1.07

[a] BUTLER, B. S.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1 p. 695, 1916.

Southeast of the fault the copper-bearing beds are probably covered by the nearly horizontal Eastern (Cambrian) sandstone (see Fig. 169). Northwest of it the Keweenawan beds dip northwest at angles of 40° to 20° or less.

The copper deposits are in the main broad tabular bodies that strike and dip with the beds. The principal productive belt, which is in the Middle Keweenawan, extends from a point near Rockland, in Ontonagon County, northeastward to a point near Eagle River, a distance of about 70 miles. Numerous veins cut across the lodes, but these are at present of no great commercial importance. The copper now mined occurs as native metal, although formerly some copper was obtained as sulphide from the crosscutting veins. The value of the ore is low, ranging at present from about 0.6 to 2 per cent. A little native silver occurs with the copper; in the ore now mined it is almost negligible.

Owing to the occurrence of the copper as the native metal the problem of beneficiation is simple. The ore is stamped in huge steam stamps and jigged or otherwise concentrated by gravity. "Lake copper" is of high grade and commands a premium in the markets.

The principal gangue minerals are calcite, quartz, chlorite (delessite), prehnite, and laumontite, but considerable quantities of analcite, orthoclase, thomsonite, apophyllite, natrolite, and other zeolites are present, with many other minerals.

The copper of the bedded deposits replaces the conglomerates and amygdaloids, fills amygdules and other openings in them, and cements small fissures in the trap series. At present the amygdaloidal deposits supply about twice as much ore as the conglomerates. The latter are mined extensively in the vicinity of Calumet.

The amygdaloidal and conglomerate deposits extend great distances along the strike;[1] the Kearsarge lode is mined almost without break for 14 miles, and other lodes are mined for 2 miles or more along their strike. They have been followed down the dip more than 1½ miles, or about 1 mile below the surface.

Copper is found at many stratigraphic horizons in the amygdaloids. Some of the lava flows are 100 feet thick or even thicker. At some places the amygdaloidal ore is at the top, at others at the bottom of a flow. In general the productive amygdaloids are mined for a width of 30 or 40 feet. At some places the amygdaloids carry copper for a width of only 3 or 4 feet; at such places they are generally unprofitable.

Although a number of conglomerate beds contain small amounts of copper, only two conglomerates, the Allouez and the Calumet, are workable. One of these, the Calumet, is the mainstay of the Calumet & Hecla Co., the greatest copper producer in the region. This conglomerate dips 39° NW. at the surface and is followed down the dip 8,100 feet, to a vertical depth of 4,748 feet. A vertical shaft about a mile from the outcrop passes through the lode at a depth of 3,287 feet. One of the Tamarack shafts reaches a depth of 5,229 feet.

The conglomerate lode is 13 feet wide at the surface and 20 feet wide in the deep workings. The upper half of the bed is richer than the lower half. The copper content of this conglom-

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[1] Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 575, 1911.

erate was about 4 per cent. near the surface, but a mile vertically below the surface it is only 1 to 1.5 per cent.

The genesis of these deposits is a vexed problem. They doubtless were formed by hot waters. Lane[1] has shown that the waters of deep levels are strong chloride solutions, chiefly calcium and sodium chlorides, much like sea water. He considers them "connate" or fossil waters of great antiquity. They are unlike the surface waters of the mines, a fact which shows that there is at present no active deep circulation. Many zeolites like those with which the ores are associated have been formed synthetically in hot solutions,[2] but generally below 200° C. F. E. Wright[3] has shown that copper and silver will be alloyed when formed above 500° C., and as these metals are not alloyed in the Lake Superior deposits it may be inferred that the temperatures of deposition there were lower.

It is certain that some of the copper was deposited in Middle Keweenawan time, for boulders in some of the conglomerates show mineralization that must have taken place before the fragments now forming the conglomerate[4] were broken from the parent ledges.[5]

As the copper ores are replacement deposits they must have formed after the associated rocks had solidified.[6] This places the formation of some of the deposits at a time after the effusion and solidification of associated diabase amygdaloids, and before the entire series was deposited.

The associated minerals, many of which are formed, so far as known, only near or above 100° C., suggest a genesis related to magmatic processes. The evidence suggests that the deposits were formed by magmatic solutions, perhaps mingled with meteoric

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[1] Lane, A. C.: Mine Waters. Lake Superior Min. Inst. *Proc.*, vol. 13, pp. 74–126, 1908.

[2] Doelter, C.: Ueber die kuenstlichkeit Darstellung und die chemische constitution einiger Zeolithe. *Neues Jahrb.*, 1890, Band. 1, pp. 118–139.

[3] Wright, F. E.: The Intrusive Rocks of Mount Bohemia, Michigan. Mich. Geol. Survey *Ann. Rept.* for 1908, pp. 361–397, 1909.

[4] Compare with description of zeolitization of traps of White River, Alaska, by Adolph Knopf (*Econ. Geol.*, vol. 5, p. 247, 1910) who noted fragments of cupriferous amygdaloid in a pyroclastic rock that overlies a cupriferous amygdaloidal bed.

[5] Van Hise, C. R., and Leith, C. K.: *Op cit.*, p. 581.

[6] Pumpelly, Raphael: The Paragenesis and Derivation of Copper and its Associates on Lake Superior. *Am. Jour. Sci.*, 3d ser., vol. 2, pp. 188–189, 243–258, 347–355, 1871.

waters, reacting on the solidified lavas and conglomerates that were above the cooling magmas. The mineralization took place before the beds were tilted, perhaps at a time when they were nearly flat-lying. This theory is not out of keeping with the observations of Lane on the composition of mine waters,[1] or those of Biddle[2] and of Fernekes[3] on the chemistry of the deposits, or those of Pumpelly,[4] Irving,[5] and Van Hise and Leith[6] on the hydrothermal alterations.

Large deposits have recently been developed in the "Nonesuch" beds. These consist chiefly of chalcocite disseminated at certain horizons in sandstone.

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[1] Lane, A. C.: Geological Report on Isle Royale, Mich. Geol. Survey, vol. 6, part 1, pp. 99—*et seq.*, 1898. The Chemical Evolution of the Ocean. *Jour. Geol.*, vol. 14, pp. 221–225, 1906.

[2] Biddle, H. C.: The Deposition of Copper by Solutions of Ferrous Salts. *Jour. Geol.*, vol. 9, pp. 430–436, 1901.

[3] Fernekes, G.: Precipitation of Copper from Chloride Solution by Means of Ferrous Chloride. *Econ. Geol.*, vol. 2, p. 580, 1907.

[4] Pumpelly, Raphael: *Op cit.*

[5] Irving, R. D.: The Copper-Bearing Rocks of Lake Superior. U. S. Geol. Survey *Mon.* 5, pp. 419–426, 1883.

[6] Van Hise, C. R., and Leith, C. K.: The Geology of the Lake Superior Region. U. S. Geol. Survey *Mon.* 52, p. 583, 1911.

CHAPTER XXIV

GOLD

Minerals	Percentage of gold	Composition
Native gold	100.0	Au
Gold amalgam	....	Au,Hg
Electrum	....	Au,Ag
Calaverite	39.5	$(Au,Ag)Te_2$
Krennerite	39.5	$(Au,Ag)Te_2$
Sylvanite	24.5	$AuAgTe_4$
Petzite	25.4	$(Au,Ag)_2Te$

MINERAL ASSOCIATIONS

Gold is one of the rarer metals in nature, and chemically it is one of the most inactive. It forms stable natural compounds with but few other elements and only with metals. Although rare, gold is peculiarly widespread; traces are found in sea water and in the ashes of plants and animals. Small amounts of metallic gold are commonly present in other metallic minerals, especially in pyrite, chalcopyrite, galena, sphalerite, and other sulphides. Some gold is intimately associated also with quartz, calcite, alunite, and other gangue minerals. A common ore is composed of quartz, pyrite, and gold, with small amounts of other minerals. The various types of hydrothermal alteration in and along gold veins are mentioned on pages 230 to 268. The wall rock may be replaced by sericite, calcite, alunite, gold, pyrite or tellurides, generally by combinations of two or more of these, the particular minerals depending upon the character of the rock, the composition of the depositing solutions, and the physical conditions at the time of deposition.

The amount of gold in its ores varies greatly. In 1912 the "dry" or siliceous ores produced in Alaska yielded $2.85 a ton in precious metals, Nevada ores yielded $14.74, and the average value of gold and silver recovered from 10,584,777 tons treated in the United States was $7.40. With improvements in mechanical concentration and in the cyanide process, it becomes possible to treat the lower-grade ores. With a few exceptions copper ores contain gold, some of them large amounts. Many silver deposits carry much gold, also. Some lead and zinc ores carry gold and silver.

GENESIS OF GOLD DEPOSITS

Gold is found in igneous rocks and in pegmatite veins, but such occurrences are of more scientific than commercial interest. Gold occurs in some contact-metamorphic deposits, and in a few it is the principal metal. As a syngenetic mineral in sedimentary beds gold is deposited mainly, if not exclusively, by mechanical processes.

Except placers, nearly all workable deposits of gold are veins and related deposits. In veins gold is deposited at all depths. In the Appalachian region gold deposits have been formed some 3 or 4 miles below the surface, and at many places the gold is associated with magnetite and pyrrhotite. In the Dahlonega district, Georgia,[1] and at Pinetucky, Ala.,[2] the gold is associated with veins having a garnet gangue. In the Black Hills, South Dakota, it is associated with garnet, actinolite, and tremolite. Many of the great gold deposits of the American Cordillera have been formed at moderate depths, as in the Mother Lode, Grass Valley, and Ophir, Cal. Other gold deposits have been formed relatively near the surface, as at Goldfield, Nev., and Cripple Creek, Colo. Gold is persistent, then, from the deep vein zone to the surface. It has been deposited in the sinters of some hot springs.

On weathering gold behaves more like iron than like copper. It is concentrated mechanically in placers, and the outcrops of its deposits are enriched by the removal of other materials more rapidly than gold. In a suitable environment, where the waters carry chlorides and the ores contain manganese, the gold will be dissolved and may be transported and reprecipitated at considerable depths.

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[1] LINDGREN, WALDEMAR: Notes on the Dahlonega Mines. U. S. Geol. Survey *Bull.* 293, p. 126, 1906.

[2] MCCASKEY, H. D.: Notes on Some Gold Deposits of Alabama. U. S. Geol. Survey *Bull.* 340, p. 36, 1908.

AGE AND ASSOCIATIONS OF GOLD DEPOSITS

Practically all the gold output of North America has been derived from veins formed by ascending hot solutions, from nearly related deposits, and from placers. The lode deposits are found in rocks of all kinds, both igneous and sedimentary, and of various ages, from pre-Cambrian to Pliocene. Many deposits are associated with granite, granodiorite, monzonite, and their porphyries, or with andesite and dacite. Some, however, are associated with alkali-rich rocks such as phonolite, and a few with gabbro and diabase. Gold veins are found also in rhyolite, basalt, and other surface lavas, but generally such rocks are found to be cut by intrusives near the veins.

Gold deposits, like those of iron, copper, and other metals, have been formed more abundantly in certain geologic periods than in others.[1]

Pre-Cambrian Deposits.—In the pre-Cambrian and probably in early Paleozoic time many gold deposits were formed in the southern Appalachian Mountains. Gold deposits also were formed in pre-Cambrian time in the Black Hills, where placer gold is found in Cambrian conglomerates. Many of the pre-Cambrian deposits formed in the deep vein zone carry garnet, actinolite, magnetite, pyrrhotite, and other minerals deposited at high temperatures. Not all the deposits are of this class, however. In the pre-Cambrian time, as later, gold deposits were doubtless formed at various depths, but because much erosion has since taken place in the Appalachian region most of the deposits remaining are but the "roots" of deposits that were once much more extensive vertically.

Cretaceous Veins of the Pacific Coast.—The most productive gold belt in the United States is along the Pacific coast, where there were great intrusions of granitic rocks in Cretaceous time. The gold deposits are found in California, Oregon, Washington, British Columbia, and Alaska. The veins are large and numerous but are mainly of low grade, the average value being about $5 a ton. Much of the production has been derived from placers. The lodes contain quartz, alkali earth carbonates, and some sericite, with subordinate chlorite. Alteration generally extends only a few feet from the lodes. These deposits are near

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[1] LINDGREN, WALDEMAR: The Geological Features of the Gold Production of North America. Am. Inst. Min. Eng. *Trans.*, vol. 33, p. 790, 1902.

the roots of veins, but in general they were formed above the zone corresponding to that which now remains of many pre-Cambrian deposits. Tabular forms are more prevalent than stockworks and reticulated masses, though in California there are many sheeted zones and "stringer lodes." In the main, however, the veins have remarkable continuity and seem to have been formed under conditions which favored development of stronger and more persistent fractures than those of the Appalachian pre-Cambrian veins. The deposits everywhere contain sulphides, though they are not abundant; silver is insignificant in quantity, and bonanzas are rare. The minerals are quartz, gold, a little pyrite, arsenopyrite, chalcopyrite, here and there galena and zinc blende, rarely tetrahedrite, telluride, and molybdenite. Gangue minerals include calcite, dolomite, siderite, and rarely barite and fluorite. Some of the veins carry pyrrhotite and albite, suggesting affiliation with deposits of the deeper zone.

Late Cretaceous or Early Tertiary Deposits.—Volcanic activities moved eastward about the end of the Cretaceous period, and in early Tertiary time there were extensive igneous intrusions in Montana, Idaho, Utah, Arizona, and Colorado. Many gold deposits are associated with the intrusives in this area, which Lindgren has designated the "central belt." The deposits of late Cretaceous or early Tertiary age occur in Montana, where they have yielded great quantities of placer gold in Alder, Confederate, and Prickly Pear gulches and on Gold Creek. The lodes from which these deposits were derived were disappointing. In this region deposits of similar age but carrying more silver than gold are found at Philipsburg, Butte, and other places. The deposits of the central belt are mainly sericitic and calcitic (page 231). They were formed at intermediate depths. Many of them carry the complex antimony or arsenic-silver minerals. Bonanzas are not uncommon.

Middle and Late Tertiary Deposits.—The Tertiary gold deposits, which form the latest group, are abundant in the Great Basin—in Nevada and portions of adjoining States. They are also developed at many places in Colorado and to some extent over other portions of the western Cordillera, where there was extensive igneous intrusion in middle and late Tertiary time. Bonanzas are characteristic, and placers are less common than in deposits of the Pacific coast type. Many of these deposits were formed near the surface, probably most of them at depths of less than a mile. Hydrothermal metamorphism extends to great distances from the veins, especially in andesite, which is a common country rock. Propylitic alteration is characteristic. It is attended by the development of chlorite, calcite, sericite, and pyrite, with the formation of adularia and devitrification of any glass present. The ores are largely silver-gold ores that contain too little lead or copper to smelt without mixing with other ores.

Typical districts of the Basin province are Tonopah, Washoe, Goldfield, Tuscarora, and Rhyolite, Nev.; and Bodie, Cal. In Colorado the deposits of Cripple Creek and some at Georgetown and Idaho Springs belong to this group. Notable examples are found also in Mexico and Central America.

SUPERFICIAL ENRICHMENT

General Features.—Unlike copper and silver, gold is insoluble in sulphuric acid. Wurtz[1] stated, in 1858, that ferric sulphate dissolves gold, and his statement has frequently been quoted in discussions of the processes of enrichment of gold deposits. Stokes[2] showed, however, that ferric sulphate will not dissolve gold, even at 200°C., except in the presence of a chloride, and its insolubility in ferric chloride and in ferric sulphate at ordinary temperatures has been verified by Brokaw.[3] Gold is dissolved in the presence of a chloride and manganese dioxide. Hydrochloric acid forms in the presence of sodium chloride and sulphuric acid, and in the presence of an oxidizing agent the hydrogen ion is removed to form water, leaving the chlorine in the so-called "nascent state." In this state its attack is vigorous. It is known that several oxides will release "nascent chlorine" at low temperatures if the solutions are sufficiently concentrated, but in moderately dilute solutions manganese oxides are the only common ones that are appreciably effective.[4]

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[1] Wurtz, Henry: Contributions to Analytical Chemistry. *Am. Jour. Sci.*, 2d ser., vol. 26, p. 51, 1858.

[2] Stokes, H. N.: Experiments on the Solution, Transportation, and Deposition of Copper, Silver, and Gold. *Econ. Geol.*, vol. 1, p. 650, 1906.

[3] Brokaw, A. D.: The Solution of Gold in the Surface Alterations of Ore Bodies. *Jour. Geol.*, vol. 18, p. 322, 1910.

[4] Emmons, W. H.: The Agency of Manganese in the Superficial Alteration and Secondary Enrichment of Gold Deposits in the United States. Am. Inst. Min. Eng. *Bull.* 46, pp. 789–791, 1910.

Experiments on the solubility of gold in cold dilute solutions were made by Brokaw.[1] The nature of these experiments is shown by the following statements, in which *a* and *b* represent duplicate tests:

(1) $Fe_2(SO_4)_3 + H_2SO_4 + Au$.
  (*a*) No weighable loss (34 days).
  (*b*) No weighable loss.

(2) $Fe_2(SO_4)_3 + H_2SO_4 + MnO_2 + Au$.
  (*a*) No weighable loss (34 days).
  (*b*) 0.00017 gram loss.[2]

(3) $FeCl_3 + HCl + Au$.
  (*a*) No weighable loss (34 days).
  (*b*) No weighable loss.

(4) $FeCl_3 + HCl + MnO_2 + Au$.
  (*a*) 0.01640 gram loss; area of plate, 383 square millimeters (34 days).
  (*b*) 0.01502 gram loss; area of plate, 348 square millimeters.

To approximate natural waters more closely, a solution was made one-tenth normal as to ferric sulphate and sulphuric acid and one twenty-fifth normal as to sodium chloride. Then 1 gram of powdered manganese dioxide was added to 50 cubic centimeters of the solution, and the experiment was repeated. The time was 14 days.

(5) $Fe_2(SO_4)_3 + H_2SO_4 + NaCl + Au$.
  No weighable loss.

(6) $Fe_2(SO_4)_3 + H_2SO_4 + NaCl + MnO_2 + Au$.
  Loss of gold, 0.00505 gram.

Although the concentration of chlorine in most of these experiments is greater than that which is found in many mineral waters, it is noteworthy that solution of gold will take place with even a trace of chlorine (see experiment 2*b*), and without much doubt these reactions will go on also in the presence of only minute quantities of manganese oxides.

The solution of gold is most extensive in the upper parts of

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[1] Brokaw, A. D.: *Op. cit.*, pp. 321–326.

[2] This duplicate was found to contain a trace of Cl, which accounts for the loss.

the oxidized zones, where most of the pyrite has been removed, for pyrite precipitates gold, and on oxidation pyrite yields ferrous sulphate, which tends to inhibit solution.

Where it is held in solution as chloride, gold is readily precipitated by ferrous sulphate. If much manganese oxide is present, however, the ferrous sulphate is immediately oxidized to ferric sulphate, which does not precipitate gold from solutions in which it is held as chloride. In the presence of manganese oxides, therefore, not only is gold dissolved in acid solution, but the conditions under which it is precipitated may be delayed. Gold may be carried in acid solution so long as the higher oxides of manganese are present. In many gold deposits manganese oxides and gold are intimately associated and without doubt have been precipitated together.

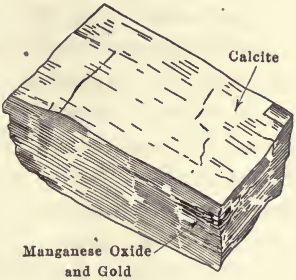

FIG. 170.—Calcite crystal that was immersed in a manganiferous acid gold solution. Gold and manganese dioxide have been precipitated together in cleavage cracks.

If a crystal of calcite is placed in an acid solution in which gold is dissolved in the presence of manganese, gold is precipitated with manganese oxide on the surface and in the cleavage cracks of the calcite crystal[1] (Fig. 170). The reactions may be stated:

$$2AuCl_3 + 3MnCl_2 + 6H_2O \rightleftarrows 2Au + 3MnO_2 + 12HCl.$$

It follows also from this experiment that gold will not be dissolved readily when calcite is present in excess.[2]

These reactions indicate processes by which gold held in acid solution in the presence of manganese salts may be precipitated in the deeper zones, together with manganese oxides, when the solutions reacting on alkaline minerals lose acidity.

In some deposits there is evidence that gold has been dissolved and reprecipitated in the surficial zone, yet the secondary gold ore carries no manganese, or at least not more than a trace of manganese compounds. Ferrous sulphate will precipitate gold even from strongly acid solutions in which manganese would still re-

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[1] BROKAW, A. D.: The Secondary Precipitation of Gold in Ore Bodies. *Jour. Geol.* vol. 21, p. 251, 1913.

[2] EMMONS, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, p. 314, 1917.

main in solution. It follows that manganese might not be precipitated with gold from acid solutions even where manganese dioxide has supplied conditions for its solution in chloride waters; but from neutralized solutions the gold and manganese would go down simultaneously. Gold is precipitated from chloride solution also by native metals, sulphides, organic matter, and many other materials.

Placers and Outcrops.—Those deposits in which enrichment in gold is believed to have taken place are, perhaps without exception, manganiferous. Inasmuch as enrichment is produced by the downward migration of the gold instead of by its superficial removal and accumulation, it follows that both gold placers and outcrops rich in gold are generally found in connection with nonmanganiferous deposits.[1] Placer deposits in the main are associated with nonmanganiferous lodes, and such lodes are generally richer at the outcrops and in the oxidized zones than at greater depths, the enrichment being due to a removal of the material associated with gold. Even under favorable conditions, however, gold is generally dissolved less readily than copper or silver and precipitated more readily than either. Consequently its enriched ores are likely to be found nearer the surface. In a manganiferous calcite gangue gold may accumulate at the very outcrop, for the solutions do not long remain acid if passing through strongly alkaline rocks. Some placer deposits, indeed, are associated with gold lodes having a manganiferous calcite gangue.

Concentration in the Oxidized Zone.—The concentration of gold in the oxidized zone near the surface, where the waters remove the valueless elements more rapidly than gold,[2] is an effective process in lodes that do not contain manganese or in manganiferous lodes in areas where the waters do not contain appreciable chloride (see Fig. 171,*a*). In the oxidized zone in some mines it is difficult to distinguish the ore which has been enriched by this process from ore which has been enriched lower down by the solution and precipitation of gold and which, as a result of erosion, is now nearer the surface. Rich bunches of ore are much

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[1] Emmons, W. H.: The Agency of Manganese in the Superficial Alteration and Secondary Enrichment of Gold Deposits in the United States. Am. Inst. Min. Eng. *Bull.* 46, pp. 813, 814–816, 1910. *Jour. Geol.*, vol. 19, pp. 15–46, 1911.

[2] Rickard, T. A.: The Formation of Bonanzas in the Upper Portions of Gold Veins. Am. Inst. Min. Eng. *Trans.*, vol. 31, pp. 198–220, 1902.

more common in the oxidized zone than in the primary sulphides of such lodes. They are present in some lodes which carry little or no manganese in the gangue and which below the water level show no deposition of gold by descending solutions. Some of them are doubtless residual pockets of rich ore that were richer than the main ore body when deposited as sulphides, but others are very probably ores to which gold has been added in the process of oxidation near the water table by the solution and precipitation of gold in the presence of the small amount of manganese contributed by the country rock. In view of the relations shown by experiments it is probable that a very little manganese will accomplish the solution of gold, but it requires considerably more manganese to form appreciable amounts of the higher manganese compounds that delay the deposition of gold by suppressing its precipitation. In the absence of larger amounts of the higher manganese compounds the gold would probably be precipitated almost as soon as the solutions encountered the zone where any considerable amounts of pyrite or other sulphides were exposed in the partly oxidized ore; for oxygenated solutions dissolve pyrite and even traces of the ferrous sulphate formed in the oxidizing reactions precipitate gold almost immediately. Many other sulphides precipitate gold very readily. Deposits showing only

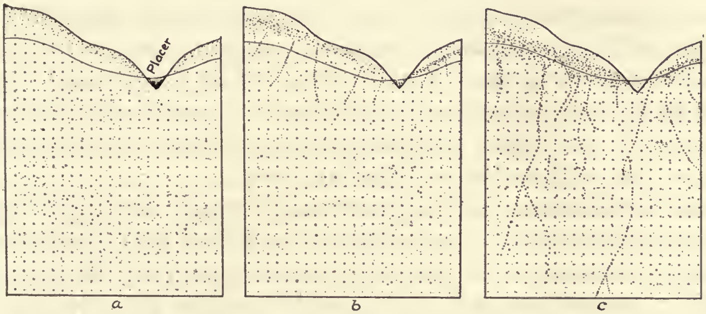

FIG. 171.—Ideal sections showing influence of manganese on secondary concentration of gold in deposits of sulphide ores. *a*, Longitudinal projection of gold vein without manganese minerals. The gold is concentrated at the surface by removal of valueless material and accumulates as placers. *b*, Longitudinal projection of gold vein with manganese minerals and with calcite or other minerals that readily reduce acidity. Some gold is dissolved but is not carried to great depth. *c*, Longitudinal projection of gold vein with considerable manganese and without minerals that rapidly reduce acidity. Gold is dissolved and reprecipitated, and some is deposited at considerable depths.

traces of manganese, presumably supplied from the country rock, are not much enriched below the zone of oxidation.

Relation of Gold Enrichment to Chalcocitization.—In several of the great copper districts of the West gold is a valuable by-product. In other deposits silver and gold are the principal metals, and copper, where present, is only a by-product. But in some of these precious-metal ores chalcocite is nevertheless the most abundant metallic mineral and constitutes several per cent. of the vein matter. In many ores it forms a coating over pyrite or other minerals. Some of this ore, appearing in general not far below the water table, is fractured, spongy quartz coated with pulverulent chalcocite. A part of it contains silver and more gold than the oxidized ore or the deeper-seated sulphide ore. Clearly the conditions that favor chalcocitization are favorable also to the precipitation of silver and gold.

Chalcocitization sets free ferrous sulphate (page 356), and even a trace of ferrous sulphate precipitates gold from acid solutions in which it is dissolved as chloride. Furthermore, chalcocite itself readily precipitates gold. It follows that gold is not precipitated by downward enrichment below the zone where chalcocite is being deposited.

Gold and silver are commonly associated in their deposits. Although gold is dissolved in chloride solutions, silver chloride is but slightly soluble, and high concentration of the two metals could not exist in the same solution. Silver chloride is slightly soluble in water, and silver may be held in small concentration in solutions in which gold also is dissolved. A mine water from the Comstock lode[1] carried 188 milligrams of silver and 4.15 milligrams of gold in a ton of solution. As ferrous sulphate and certain sulphides precipitate both gold and silver from acid solution, alloys of these metals might form as secondary minerals. As ferrous sulphate is released in the chalcocitization of pyrite, the secondary ores of gold and silver can be deposited simultaneously with chalcocite.

Tellurides.—Petzite, sylvanite, krennerite, and calaverite are tellurides of gold and silver, the precious metals being present in varying proportions. All are primary.

Summary.—The materials whose presence is favorable, if not essential, for gold enrichment are (1) chloride solutions, (2) iron

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[1] Reid, J. A.: The Structure and Genesis of the Comstock Lode. Cal. Univ. Dept. Geol. *Bull.*, vol. 4, No. 10, p. 193, 1905.

sulphides, (3) manganese compounds. Where these materials exist and where no very effective precipitant is at hand and erosion is not too rapid, gold placers are rarely formed, and outcrops of gold ores are likely to be less rich than the ores that lie deeper (Fig. 171, *c*). Where these materials exist and where the lodes are fractured, gold will migrate downward in solution. Many minerals will precipitate gold, but in the presence of some, including calcite, siderite, rhodochrosite, pyrrhotite, chalcocite, nepheline, olivine, and leucite its precipitation is especially rapid. In deposits that carry appreciable quantities of these minerals in ore or wall rock the downward migration of gold is delayed, and gold bonanzas are likely to be formed at or very near the surface (Fig. 171, *b*). Under these conditions, also, placers may be produced, even from manganiferous lodes. In a gangue of adularia, sericite, and quartz, with pyrite, chalcopyrite, galena, and sphalerite, gold may be carried downward several hundred or even a thousand feet, but this depth should be regarded as nearly the maximum and exceptional. Gold is readily precipitated by many common minerals; it will generally migrate slowly in ground water.

GOLD PLACERS

General Features.—A large part of the world's gold has come from placers, which now yield about 20 per cent. of the annual production. Placer deposits as a rule are the most easily discovered of all metalliferous deposits, and because their product is so easily transported and marketed the placers are commonly the first resources of a region to be exploited. The lure of gold has resulted in the exploration and development of many a new country.

As a land surface is worn away in regions where conditions are unfavorable for solution, gold contained in veins and veinlets or disseminated in the rock tends gradually to become concentrated at the surface. Some of it may remain practically in place. The rotten outcrops (saprolites) of many veins in the southern Appalachians were washed for gold.[1] As erosion goes on the gold-bearing mantle rock of a deposit on a slope will gradually settle downhill, constituting an eluvial deposit. As erosion is continued further, however, the gold ultimately finds lodgment

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[1] Becker, G. F.: Gold Fields of the Southern Appalachians. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 3, p. 289, 1895.

in streams together with sand and gravel. Such accumulations constitute the principal placer deposits.

In placer mining commonly a box-like trough, called a sluice, is fitted on the bottom with movable cross pieces or riffles. Although tons of rock may be washed through the sluice, nearly all the gold collects in the pockets behind the riffles. The bed of a stream acts much like the placer miner's sluice. The gold sinks to the bottom and remains on bedrock, especially in joints and seams or in low places in the bed. As gold (specific gravity 15.6 to 19.3) is about six to seven times as heavy as rock (specific gravity 2.5 to 3), it will sink, except the very finest dust, which may be carried away. The coarser gold generally remains in gulches and creeks near its source, forming gulch and creek gravels; the finer gold may be carried to rivers and supply gold for river gravels; some gold may be carried even to the sea.

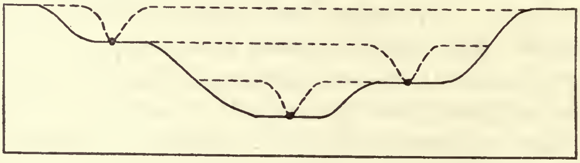

FIG. 172.—Sketch showing placer deposits on terraces of a stream. These were formed when the terraces were parts of the flood plain of the stream. (*After Tyrrell.*)

Where a shore line is receding by wave action the gold may be concentrated along the beaches as beach placers or marine placers. At Nome, Alaska,[1] placer deposits occur both along streams and along the beach.

Placers formed in gulches, in beds of rivers, or on the sea shore may be elevated by general uplift of the region to levels above the present drainage lines or along the coast far above sea level. As streams approach grade they meander in their flood plains, and gold contained in flood-plain deposits may be distributed over wide areas. In the normal history of erosion a stream will cut below its flood plain, and the abandoned flood plain will later appear high above the stream as a terrace.[2] Some deposits

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[1] COLLIER, A. J., HESS, F. L., SMITH, P. S., and BROOKS, A. H.: The Gold Placers of Parts of Seward Peninsula, Alaska. U. S. Geol. Survey *Bull.* 328, 1908.

[2] CHAMBERLIN, T. C., and SALISBURY, R. D.: "College Geology," pp. 191–194, 1909.

worked for placer gold are far above the present streams (Fig. 172).

Placer deposits may be buried under later deposits. Lava flows that are extravasated upon a rugged surface containing placers generally cover the lower areas—the bottoms of valleys. The streams that subsequently flow over the lavas will take new courses, and after they have sunk their beds below the ancient beds that were filled by the lavas the gold deposits will crop out on hillsides where the ancient channels are crossed by the later ones. Such ancient gravels in California have yielded much gold. As the land surface is eroded the gold in the old channels is carried down into present stream valleys. Thus the gold-bearing gravels in present channels may represent not only the waste of lodes that are now being eroded, but reconcentrations from ancient placers that were recently exhumed.

Scour and Fill.—There is a strong tendency for gold to work downward in gravels. It may halt at a stiff clay seam in the gravel bed, or it may descend to the bedrock and be concentrated in joints and fractures of the rock. Cross-currents, eddies, and whirlpools are common features of streams, and normal stream erosion is attended by extensive reassortment of stream deposits.

The development of potholes is common in swift streams, and even sluggish streams scour the loose unconsolidated material of their beds. Soundings in rivers show that deep holes are sunk in fluvial deposits by running water. Even the more sluggish streams that are filling their channels will continually reassort the material deposited in them by dropping the coarse and picking up the fine. In flood time material is deposited on the flood plain, but at the same time material in the main or central channel may be picked up and carried downstream because the velocity and volume of the stream are greater than during low water. At Nebraska City, Nebr.,[1] the scouring action is known to extend to depths of 70 to 90 feet. Holes scoured out at one time will be filled later. Thus material is continually agitated and shifted downstream, and any gold present tends to settle to bedrock. In gold-bearing gravels the gold is generally greatly concentrated on bedrock. Dredging or sluicing operations yield the greatest profit from the material lying within a few inches of the bottom of the gravel bed. It is common prac-

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[1] Chamberlin, T. C., and Salisbury, R. D.: "College Geology," pp. 184–185, 1909.

tice, indeed, to dredge out the bedrock in order to obtain the gold deposited in its crevices.

Where the grade of a swift stream becomes lower gravels with contained gold will accumulate. Alluvial fans, gravel plains, or any other depositional features may be the sites of placer gold.

Minerals Associated with Gold in Placers.—The common associates of the gold may be hard or soft, heavy or light, brittle or malleable. They have one feature in common—they are not readily dissolved in ground water nor in stream waters. Stream gravels are made up of various materials. Minerals that are commonly found with placer gold are the heavier minerals that are stable—magnetite, ilmenite, hematite, pyrite, garnet, etc. In regions containing deposits of cassiterite, monazite, zircon, platinum, or diamonds, these minerals also will accumulate in placers. Silver, mercury, copper, and lead are alloyed with gold, and considerable silver may be present with gold in placers that have not moved far from their sources. These metals, however, are more easily dissolved than gold and rarely accumulate in large quantities.

Solution of Gold in Placer Deposits.—Where acid waters containing sodium chloride attack gold in the presence of an oxidizing agent, such as manganese oxide, gold will be dissolved. But waters of streams normally contain very little sodium chloride, and by the processes of sedimentation the light powdery manganese oxides are generally separated from the heavier particles of gold. Moreover, acid waters are neutralized by nearly all minerals, and neutral waters do not dissolve gold. Organic matter also is generally present near the surface and in streams, and it would cause any dissolved gold to be precipitated and inhibit its solution. Thus the normal conditions are adverse to the extensive migration of gold in placer deposits by solution and redeposition, although under exceptional conditions such migration probably takes place to a minor extent.

Ground waters attack other metals more readily than gold. Silver, lead and copper are dissolved from minerals in which they are associated with gold. Thus the gold in placer deposits will generally be purer than the gold of the lodes from which it is derived, and normally the farther it is from its source and the finer its state of subdivision the purer it will be.[1]

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[1] Becker, G. F.: Gold Fields of the Southern Appalachians. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 3, p. 292, 1895.

Relation of Gold Placers to Gold Lodes.—Where gold lodes are exposed it is reasonable to expect placers, and where placers have been found the search for the source of their gold suggests interesting possibilities for prospecting. An experienced prospector will pan the gravels of gulches that drain a region which contains gold deposits and will seek gold lodes in a region which contains gold-bearing gravels. Either the placers or the lodes may be found first; placer gold is easily discovered. It is common practice to follow up a stream, panning it at intervals and to scrutinize the surrounding country carefully where "colors" suddenly cease to appear. This method has proved effective also in prospecting hill slopes for gold lodes, especially in regions that have not been glaciated. The mantle rock is panned at intervals, and a line may be found below which it contains gold and above which gold is absent. Trenching across such a line may disclose a gold-bearing lode.

Not all gold lode deposits, however, have associated placers. In some regions gold is dissolved and carried downward in solution, enriching the deposit below. Even where gold is not dissolved it is not invariably concentrated in gravels. It may be so finely divided that it is carried away in the drainage. In panning some deposits a film of gold may be seen floating on top of the water in the pan. Gold as fine as that could easily be carried away by streams and scattered. Placers are not developed from some gold deposits, because the primary ore shoot did not reach the surface and no auriferous rock has yet been eroded. Glacial erosion may remove all mantle rock and stream gravels from lodes in mountainous countries. In some regions fine flaky gold may have been blown away by winds.

Conversely, in some regions that contain placer deposits no workable gold lodes have been discovered. Where gold is not dissolved from its deposits weathering and erosion are generally very efficient processes in the mechanical concentration of gold. Hundreds or even thousands of feet of material may be eroded from a region, the rock being carried away in streams, whereas the heavier gold remains behind to enrich gravels near the deposits. In some regions the gold in gravels has been concentrated from many veins and veinlets that are too small and too low in grade to be worked underground. Many quests for the "mother lodes" in regions containing valuable placers have proved disappointing.

Eolian and Glacial Deposits Containing Gold.—Where rocks are deeply decayed in arid countries where strong winds blow, the lighter particles may be blown away from outcrops of deposits, leaving the heavy material in a more concentrated state. The deposit becomes enriched in the coarse gold that is left behind. Placers have formed in western Australia by such processes.[1]

When glaciers erode a gold-bearing area the mantle rock, gravel and loose material at outcrops of lodes will be carried away in the ice and any gold it contains will become incorporated in the drift. There is very little sorting, however, and comparatively few glacial deposits are valuable except where the material has been worked over by running water.

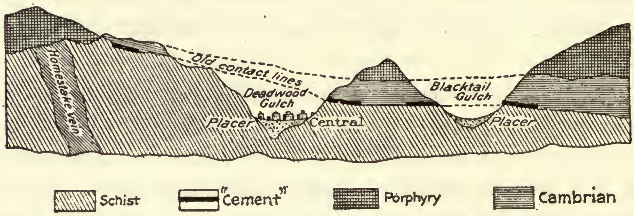

FIG. 173.—Geologic section of Homestake vein, Black Hills, South Dakota. The "cement" mines are Cambrian placers. (*After Devereux.*)

Buried Placers.—Not only are placer deposits being formed today, but they have been formed where conditions were favorable during and since pre-Cambrian time. Becker[2] mentions buried placers in the southern Appalachian region and in the Bald Mountain region, Wyoming, and states that the Triassic and Cretaceous in California contain placers. In the Black Hills, which are famous for their buried placers (Fig. 173), the Cambrian basal conglomerate and sandstone rest unconformably above the pre-Cambrian schist series that contains the Homestake lode, and in the conglomerate are found rounded grains of gold, evidently derived from the pre-Cambrian deposits. Associated beds

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[1] HOOVER, H. C.: The Superficial Alteration of Western Australian Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 28, pp. 762–763, 1899.

RICKARD, T. A.: The Alluvial Deposits of Western Australia. Am. Inst. Min. Eng. *Trans.*, vol. 28, pp. 490–537, 1899.

[2] BECKER, G. F.: The Witwatersrand Banket, with Notes on Other Gold-Bearing Pudding Stones. U. S. Geol. Survey *Eighteenth Ann. Rept.*, part 5, p. 181, 1897.

contain Cambrian marine fossils. The deposits are believed to have been formed along an ancient shore.[1]

When they were worked out the gold was found to be concentrated near the bottom of the gravel beds, as in most placers now in process of formation. Becker mentions many other gold-bearing conglomerates in America, Australia, and South Africa. The presence of heavy residual minerals, the accumulation of the gold in the lower portions of the gravel beds, and the rounding of the particles of gold are fairly constant characteristics of buried placers.

Where surfaces sink slowly below sea level and are covered by marine deposits any gold present on the sunken land surface will be washed over by the waves. Thus the stream gravels are likely to be spread out as beach gravels. It is not surprising that marine littoral rather than fluviatile deposits predominate among the ancient gravels that have been buried in the sea.

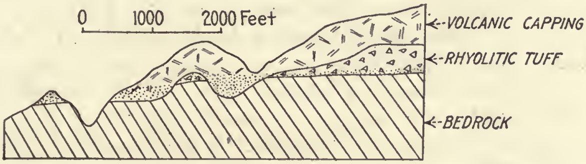

FIG. 174.—Section of Swift Shore mine, Placer County, California, showing Tertiary deposits (dotted portions) buried below lava capping. (*After Browne.*)

Where land sediments or lavas cover stream beds, the stream placers will be preserved. The most productive buried placers of North America are the Tertiary gravels of California, which, according to Lindgren[2] have yielded about $300,000,000. This region in early Tertiary time was less rugged than it is today (Fig. 174), and on its gentle surface gold accumulated in streams from the weathered lodes near by. The gravel beds were covered with rhyolite tuffs, andesitic breccia, and basalt, in places as much as 1,500 feet deep. Later the country was elevated, and deep canyons were sunk in its surface. The new drainage lines

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[1] DEVEREUX, W. B.: The Occurrence of Gold in the Potsdam Formation, Black Hills, Dakota. Am. Inst. Min. Eng. *Trans.*, vol. 10, pp. 465–475, 1882.

IRVING, J. D.: Economic Resources of the Northern Black Hills. U. S. Geol. Survey *Prof. Paper* 26, pp. 98–111, 1904.

[2] LINDGREN, WALDEMAR: The Tertiary Gravels of the Sierra Nevada of California. U. S. Geol. Survey *Prof. Paper* 73, p. 81, 1911—Mineral deposits, p. 206, New York, 1913.

did not follow the former ones, and the ancient gravel beds where crossed by later canyons are now exposed, some of them hundreds of feet above present streams. As the canyons are widened, gold in the ancient gravels is reconcentrated in the present gulches, where it mingles with material that is accumulated from the weathered outcrops of the lodes.

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WITWATERSRAND AURIFEROUS CONGLOMERATES

The auriferous conglomerates of Witwatersrand, Transvaal, South Africa,[1] which are the most productive gold deposits of

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[1] Hatch, F. A., and Corstorphine, G. S.: Petrography of the Witwatersrand Conglomerate. South Africa Geol. Soc. *Trans.*, vol. 7, 1904.

Hatch, F. A.: The Conglomerate of the Witwatersrand, in Bain, H. F., and others: "Types of Ore Deposits," pp. 202–218, San Francisco, 1911.

the world, yield about $160,000,000 annually. The country is a hilly area of crystalline schists (Swaziland schists) and intruding granites upon which rest unconformably slates, quartzites, and conglomerates belonging to the Witwatersrand system, which is probably also pre-Cambrian (Fig. 175). Above the Witwatersrand strata are conglomerates, lavas, and breccias of the Ventersdorp system; above the Ventersdorp unconformably is the Potchefstroom system, which is overlain (also unconformably) by the Table Mountain sandstones, of Devonian age. Higher still in the series are the coal-bearing Karoo beds, which are probably of Carboniferous age. The Witwatersrand system, which contains the principal ore bodies, forms a large syncline in which the beds dip at high angles.

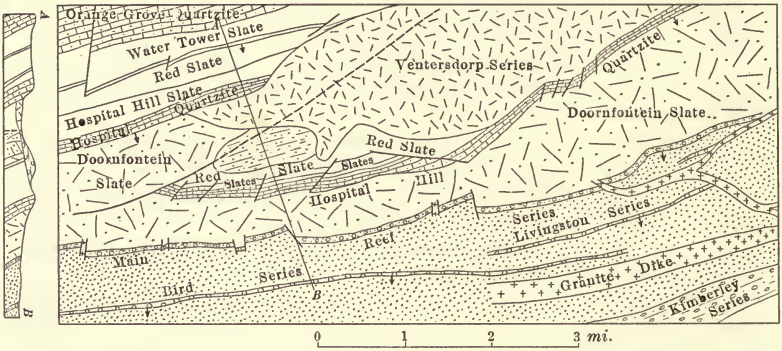

Fig. 175.—Plan and cross-section of part of Witwatersrand region, South Africa. (*Based on map by Hatch.*)

The rocks composing the Witwatersrand system consist of conglomerate, grit, quartzite, and slate. The conglomerates contain round and subangular fragments of quartz and quartzite in a matrix of quartz grains, the whole cemented by secondary silica. The quartzites are made up of quartz sand, thoroughly indurated by pressure and deposition of secondary silica. The slates consist largely of minute quartz fragments and sericite. The Witwatersrand beds are faulted and crossed by diabase dikes.

The principal gold deposits are in the upper Witwatersrand series, which is predominantly quartzite but contains four well-defined conglomerate zones, grouped as follows:

4. Kimberley series.
3. Bird Reef series.
2. Livingstone Reef series.
1. Main Reef series.

These series contain numerous beds of conglomerate and sandstone that carry gold. The Main Reef series has been worked more or less continuously for a distance of 46 miles.

In the Central Rand (the district near Johannesburg) the bulk of the gold is obtained from the Main Reef leader and from the South Reef. The conglomerates of the Main Reef consist mainly of rolled fragments of quartz pebbles, with fragments of quartzite, banded chert, and slate. The pebbles, which are worn smooth and round, lie in a matrix which originally consisted of quartz sand but which by the deposition of silica has been converted into a compact mass of quartz on freshly fractured surfaces of which even the boundaries of the pebbles are difficult to identify. Besides the quartz pebbles and the quartz sand, the only other constituents of the matrix that are undoubtedly original are zircon in microscopic crystals and chromite and iridosmine in rounded grains.

The minerals later than the quartz pebbles include chloritoid, sericite, calcite, tourmaline, rutile, pyrite, marcasite, pyrrhotite, chalcopyrite, zinc blende, galena, stibnite, cobalt and nickel arsenides, graphite, and gold telluride.

The origin of the gold in the Rand conglomerates is still in doubt. Gregory,[1] Becker,[2] and others have maintained that it is of placer origin, formed by concentration from the Swaziland schists, which carry stringers of quartz and gold. They state that the gold is concentrated in the lower parts of the beds and attribute its angular or crystalline condition to recrystallization, which would obliterate rounded surfaces of the minute particles of gold that predominate in the conglomerates. Facts that are urged as opposed to the theory that the gold was carried into the conglomerates by hot solutions are: an absence of hydrothermal metamorphism, a fairly regular distribution of gold in the con-

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[1] Gregory, J. W.: The Origin of the Gold in the Rand Banket. *Econ. Geol.*, vol. 4, pp. 118–129, 1909.

[2] Becker, G. F.: The Witwatersrand Banket, with Notes on other Gold-Bearing Pudding Stones. U. S. Geol. Survey *Eighteenth Ann. Rept.*, part 5, p. 169, 1897.

glomerate, and an absence of gold in wall rock along fractures and of cross-channels of gold ore.

On the other hand, some of the closest students of the area[1] believe that the gold was brought into the conglomerate in solution, together with other metallic minerals, among them pyrite, sphalerite, galena, and many other sulphides. Some see a generic relation between the gold deposits and diabase dikes that cut the ore-bearing beds. A third hypothesis is that there has been some infiltration of mineral-bearing thermal waters since the gold was deposited as placers.

GOLD LODES

Porcupine, Ontario.—The Porcupine gold district,[2] in northern Ontario, about 100 miles northwest of Cobalt, was discovered in 1908. It lies about 1,000 feet above the sea and is an area of low relief and wooded but not particularly swampy. The surface is covered thinly with clay, sand, and boulder clay. The oldest formation is the Keewatin, consisting of volcanic rocks and their metamorphosed representatives. This formation is more highly schistose than it is at Cobalt. The prevailing rock at Porcupine is a green igneous rock (mainly basalt) which is cut by dikes and other masses of quartz porphyry. Associated with the Keewatin also are sedimentary rocks, including iron-bearing jaspilites, iron carbonate rocks, and limestone. Above the Keewatin are Huronian quartzite and slate, altogether at least 400 feet thick. This series is tilted and locally rendered schistose. Granite (Laurentian) is intruded in the Keewatin; possibly some of the granite is intruded in the Huronian also, but as granite pebbles are found in the Huronian sediments, at least some of the granite is older

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[1] Hatch, F. A., and Chalmers, J. A.: "The Gold Veins of the Rand," London, 1895.

Hatch, F. A.: The Conglomerates of the Witwatersrand Banket, in Bain, H. F., and others: "Types of Ore Deposits," pp. 202–219, San Francisco, 1911.

Hatch, F. A., and Corstorphine, G. S.: Petrography of the Witwatersrand Conglomerate. Geol. Soc. South Africa *Trans.*, vol. 7, part 3, 1904.

[2] Burrows, A. G.: The Porcupine Gold Area, Ontario Bur. Mines. *Twenty-fourth Ann. Rept.*, part 3, 1915.

Hore, R. E.: The Nature of Some Porcupine Gold Quartz Deposits. Canadian Min. Inst. *Jour.*, vol. 14, p. 171, 1911.

Knight, C. W.: Mineral Associations at Porcupine. *Min. and Sci. Press*, April 15, 1911.

than the Huronian. Both Keewatin and Huronian are intruded by diabase dikes.

The ore deposits (Fig. 176) are veins and great irregular masses of schist seamed and impregnated with quartz and gold. Some of the deposits crop out conspicuously, among them the Dome and West Dome, so called from the shape of the outcrops at the places of discovery. The domes on the Dome property were about 100 by 125 feet. The deposits occur in both the Keewatin and Huronian rocks, and generally the lodes cut across the schistosity. The lodes range in attitude from horizontal to vertical

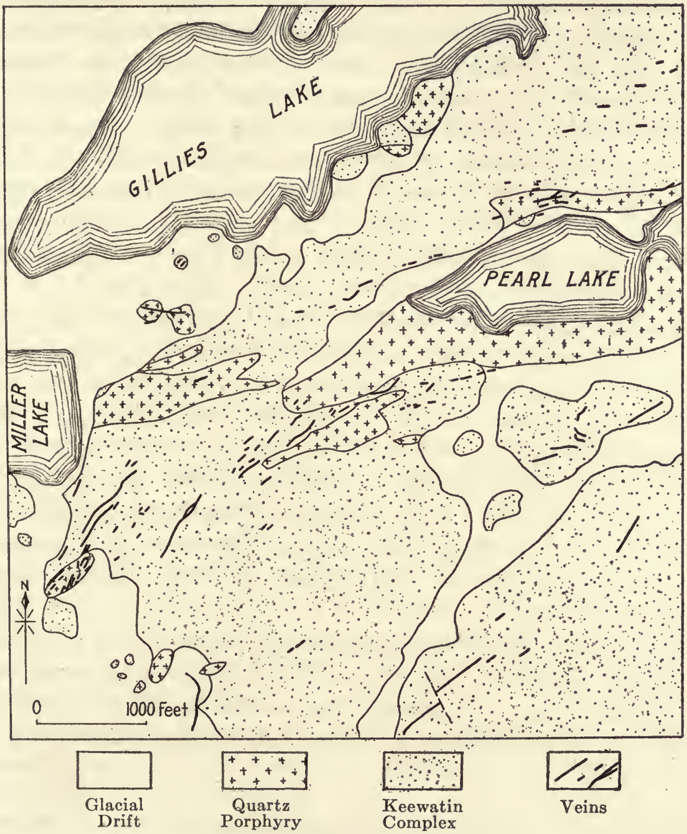

Fig. 176.—Geologic map of part of Porcupine district, Ontario. (*Based on map by Burrows and Hopkins.*)

and show a strong tendency to parallelism. The Hollinger group strikes northeast; the Dome group nearly east. Spectacular showings occur on many properties, but these are limited to small portions of the veins. Considering the irregular character of the veins and the large quantity of country rock mined, the ore is of low grade.

Besides quartz and pyrite the veins carry feldspar, tourmaline, and carbonates. The quartz of the Hollinger mine contains liquid and gas inclusions. Copper pyrite, galena, zinc blende, and pyrrhotite are found in some veins. Locally the ore is fractured and cemented with quartz and pyrite. These veins were probably formed at great depths and under high pressures, as is suggested by the presence of tourmaline and gas inclusions in the quartz. Burrows[1] believes that they are closely related to granitic intrusions. Near Night Hawk Lake are aplite dikes with fine veinlets of quartz which contain a little gold.

Southern Appalachian Region.—A belt of ancient rocks, consisting of crystalline schists and granites and other igneous rocks, extends from Alabama northeastward to Maine. In this belt several small deposits of gold have been found in Maine, New Hampshire, and several other States, but none north of Virginia has produced much gold. Valuable deposits are located in Alabama, Georgia, and the Carolinas. Gold has been mined in the southern Appalachians since early in the nineteenth century. The total production is $50,000,000, of which placers have yielded $30,000,000.

The southern Appalachian gold-bearing region[2] has a very complex geologic history. The rocks are of Archean, Algonkian, and early Paleozoic age. The gold deposits are far from uniform in character. Some of them have quartz and garnet gangue; others

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[1] *Op. cit.*, p. 20.

[2] Becker, G. F.: Gold Fields of the Southern Appalachians. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 3, pp. 250–331, 1895.

Graton, L. C., and Lindgren, Waldemar: Reconnaissance of Some Gold and Tin Deposits of the Southern Appalachians. U. S. Geol. Survey *Bull.* 293, 1906.

McCaskey, H. D.: Notes on Some Gold Deposits of Alabama. U. S. Geol. Survey *Bull.* 340, p. 36, 1908; U. S. Geol. Survey *Mineral Resources*, 1908, part 1, pp. 645–681, 1909.

Taber, Stephen: Geology of the Gold Belt in the James River Basin, Virginia. Va. Geol. Survey *Bull.* 7, pp. 1–271, 1913.

are simple quartz-pyrite-gold veins; but none are of the antimony-silver-gold type that is so conspicuously developed in the West.

The Appalachian gold veins are almost uniformly of low grade. As stated by Lindgren, they were probably formed, in the main, 3 or 4 miles below the surface at the time of deposition. Many of them are in mica schist and other crystalline rocks, and some are closely associated with granitic intrusions. Some of them are cut by diabasic intrusives, presumably later than the ore. The minerals include quartz, sericite, biotite, fluorite, gold, pyrite, galena, zinc blende, pyrrhotite, chalcopyrite, and magnetite.

Few of these deposits have been extensively explored in depth, and data respecting the vertical distribution of the gold are therefore meager. Many of them are profitable near the surface, partly by reason of the rotten condition of the rock, which renders it more easily worked, and partly because gold is accumulated or enriched by the removal of valueless material. At the Haile mine, near Kershaw, S. C., the deposits are in quartz-sericite schist and metamorphosed igneous rocks. Large diabase dikes cut the schist, and near them the ore bodies are developed. These dikes, however, are probably later than the ore. According to Graton, the limit of profitable mining is in general less than 200 feet below the limit of complete oxidation. In this zone scales of pyrite and free gold, probably secondary, are found in joint cracks. At Dahlonega, Ga., auriferous veins of quartz and garnet, with mica and hornblende, are inclosed in schist. These veins, particularly the decomposed surface outcrops, have produced considerable gold. They are lenticular and in part replace the wall rocks.

Certain ore deposits of Alabama comprise fissure veins in granite and lenticular bodies in schists. The principal minerals are quartz, pyrite, and gold. Garnet is found in the vein quartz at Pinetucky. Weathering extends to water level, which lies 40 to 80 feet below the surface. The ores are oxidized above this level and are generally free milling, but the ore so far obtained below this level is not profitably amalgamated. The deposits are fairly regular in width and tenor, and no evidences of enrichment below the water level are recorded.

The copper deposits of Ducktown, Tenn., carry a little gold (page 390)

Black Hills, South Dakota.—The Black Hills of South Dakota[1] yield annually about $7,500,000 in gold, considerable tungsten and silver, and some lead. The Homestake Mining Co., with associated companies, according to Blackstone,[2] to the end of 1915 had produced gold valued at $141,610,382.38. In 1915 it produced 1,573,822 tons of ore valued at $6,428,786.56, or $4.08 per ton.

ORE SENT TO GOLD AND SILVER MILLS IN SOUTH DAKOTA IN 1915

Process	Ore short tons	Gold in bullion (fine ounces)	Silver in bullion (fine ounces)
Amalgamation	1,573,822	228,315.55	63,554
Cyanidation	[a]1,869,248	127,901.81	132,806
		356,217.36	196,360

[a] Includes 1,554,472 tons of tailings from part of ore amalgamated.

The Black Hills constitute a domical uplift, rising above the Great Plains. The central peaks are of pre-Cambrian schists. They slope gradually outward to a rim of Paleozoic rocks that dip away from the hills. The sedimentary rocks (Fig. 177), including those as late as Cretaceous, are cut by many varieties of igneous dikes, stocks, and laccoliths. Alkali-rich rocks such as syenite porphyry and phonolite are represented. As the Tertiary (Oligocene?) beds at Lead contain pebbles of the porphyries the latter are presumably early Tertiary.

The deposits are (1) gold deposits in pre-Cambrian schists; (2) ancient placers in the Cambrian basal conglomerate; (3) siliceous gold ores replacing thin calcareous beds in the Cam-

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[1] IRVING, J. D., EMMONS, S. F., and JAGGAR, T. A.: Economic Resources of the Northern Black Hills. U. S. Geol. Survey *Prof. Paper* 26, 1904.

SHARWOOD, W. J.: Analyses of Some Rocks and Minerals from the Homestake Mine, Lead, S. D. *Econ. Geol.*, vol. 6, p. 729, 1911.

DEVEREUX, W. B.: The Occurrence of Gold in the Potsdam Formation, Black Hills, Dakota. Am. Inst. Min. Eng. *Trans.*, vol. 10, p. 496, 1882.

PAIGE, SIDNEY: Pre-Cambrian Structure of the Northern Black Hills, South Dakota, and Its Bearing on the Origin of the Homestake Ore Body. Geol. Soc. America *Bull.*, vol. 24, pp. 293–300, 1913.

[2] BLACKSTONE, RICHARD: A History of the Homestake Mine, South Dakota. *Min. and Eng. World*, July 15, 1916, pp. 99–102; South Dakota School of Mines *Pahasapa Quart.*, June, 1916, pp. 16–30.

brian; (4) gold-bearing replacement veins in Carboniferous rocks; (5) silver-lead replacement veins in Cambrian and Carboniferous rocks; and (6) recent placers.

The pre-Cambrian ores of the Homestake belt (Figs. 178, 179) are in a belt 3 miles long and 2,000 feet wide. The rocks are quartzites and mica schists (metamorphosed sediments) and amphibolites. Pre-Cambrian granite crops out not far away. The minerals of the ore are quartz, dolomite, calcite, pyrite, arsenopyrite, pyrrhotite, and gold, with which are associated the minerals of the schist—quartz, orthoclase, hornblende, biotite, garnet, tremolite, actinolite, titanite, and graphite. The ore bodies are cut by many dikes of porphyry but apparently have not been much affected by them. The ores, though of low grade, are very profitable. Some of the ores at the surface

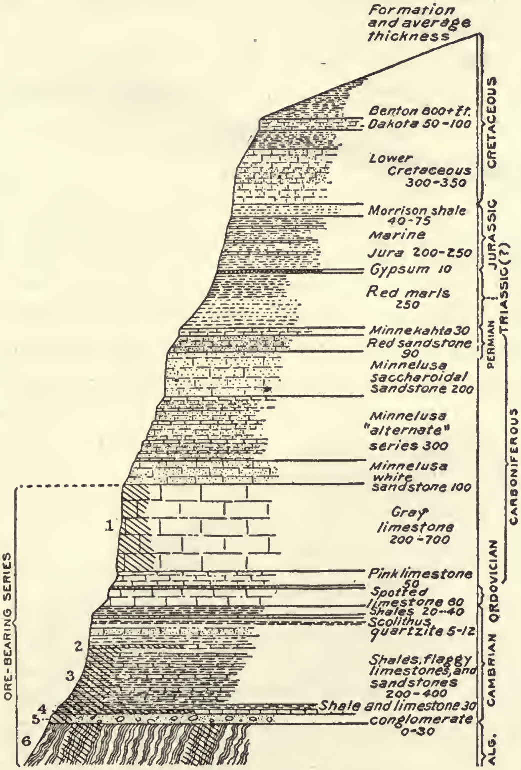

FIG. 177.—Generalized columnar section of northern Black Hills, South Dakota. (*After Jaggar, U. S. Geol. Survey.*)

were below the average in tenor, but other surface ores were two or three times as rich as the average. The valuable minerals extend downward as far as exploration has gone and are fairly uniform to depths 2,000 feet or more below the surface. In general enrichment by surface leaching is subordinate.

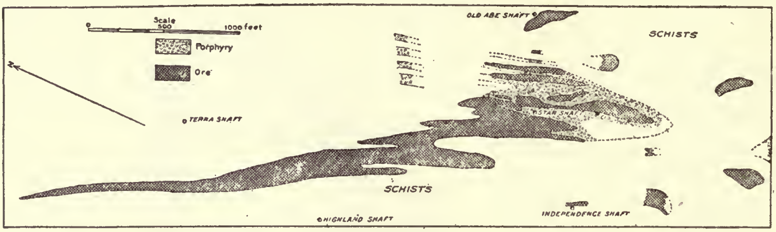

Fig. 178.—Plan of Homestake ore bodies on 300-foot level, Black Hills, South Dakota. (*After Irving, U. S. Geol. Survey.*)

The schists represent rocks of various types intensely metamorphosed by pressure. The predominating rock associated with the ore appears to be metamorphosed calcareous slate. The garnet, as shown by Irving, is generally broken and shattered, and the ore-bearing rock is highly contorted. The mineral association suggests formation at great depths.

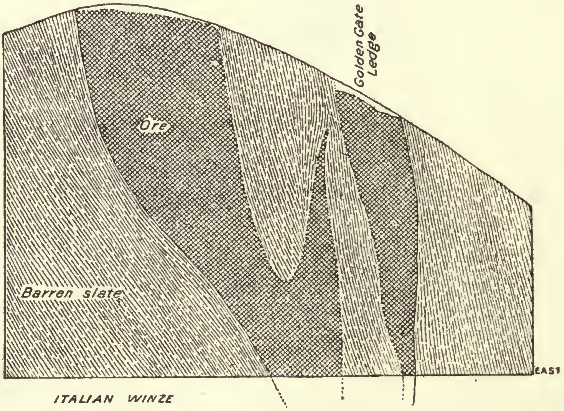

Fig. 179.—Section Homestake ore body, Father de Smet mine, Black Hills, South Dakota. (*After Irving, U. S. Geol. Survey.*)

The deposit at the Clover Leaf mine, 7 miles southeast of the Homestake mine, is a "saddle reef" in schists.

Near the Homestake mine are flat-lying conglomerates at the base of the Cambrian that contain considerable detrital gold, evidently derived from the Homestake deposits. The general relations are shown by Fig. 173. According to Irving, some pyrite has developed in some of the Cambrian placers (No. 5 in Fig. 177) since they were formed.

Valuable ore bodies were formed also in the Tertiary period. The chief of these are long, flat-lying ribbons of ore in the Cambrian, not far above its base. These have been termed "refractory siliceous ore" and "Potsdam" ore. Some of these deposits are nearly 1 mile long; they are from 10 to 300 feet wide and have an average thickness of about 6 feet. At the base of the Cambrian series is a conglomerate which grades upward into quartzite. Above the quartzite is a dolomite bed about 6 feet thick, and this is succeeded by 300 feet of shale, sandstone, and limestone. The siliceous gold ores occur extensively at two horizons—one in the lowest dolomite (No. 4, Fig. 177) and one about 25 feet below the "Scolithus" bed (No. 2, Fig. 177). The ribbons of ore are capped by blue shale. The minerals are pyrite, quartz, fluorite, gold, and some silver. As shown by Irving, they are found where the limestone beds are crossed by small fractures called verticals. Although these are generally very thin they are closely spaced, especially where the ribbons are wide. These deposits are in the areas intruded by the porphyries and are probably genetically related to them. They are classic examples of ribbons of ore formed at intersections of fissures with favorable beds. The fractures pass through the quartzite and some of them pass upward into shale. The metallizing solutions, which spread out and deposited large bodies of ore in the limestone, had little effect on the quartzite and shale.

Gold-silver replacement veins in Carboniferous rocks are found near Ragged Top, a laccolithic body of phonolite. The lodes are silicified brecciated zones in limestone. The minerals are pyrite, opaline silica, fluorite, and tellurides (probably sylvanite).

Silver-lead deposits in the Cambrian and Carboniferous rocks were formerly productive. Some are replacement deposits along fractures in sedimentary rocks and porphyries.

Near Camp Carbonate irregular dikes and sills of porphyry are intruded in Carboniferous limestone. Irregular bodies of carbonate and galena ore have formed by replacement.

Recent placers that have developed from older deposits are found along the present streams. Tungsten deposits are extensively mined in the Cambrian sedimentary beds. These are mentioned on page 525.

California Gold Belt.—The California gold belt extends northwestward, with some interruptions, through the length of the State and continues northward into Oregon but disappears beneath Tertiary lavas, to reappear in British Columbia and Alaska. The lodes, with associated gold deposits of the same general type and placers derived from them, have produced over $1,300,000,000 in gold.

The geologic history of this region is long and varied. The lowest series in the geologic column is a greatly folded and metamorphosed complex consisting of Paleozoic sedimentary rocks and interbedded lavas, called the Calaveras formation. Above this complex are Jurassic and Triassic rocks, less intensely folded than the Calaveras. Intruded into these is an enormous granodiorite batholith which forms the main mass of the range. On and near the boundary of the central intrusive mass are many smaller bodies of granodiorite, diorite, and gabbro. These are doubtless of about the same age and of similar origin. As the Mariposa formation (Jurassic) is intruded by the granodiorite, and as the Chico (Cretaceous) is not intruded by it, the age of the batholith is known to be early Cretaceous.

The gold deposits[1] are notably sparse in the central granodiorite belt but are clustered in and around the smaller intruding bodies, especially on the west slopes of the Sierra. The deposits are veins. Some of them are arranged in conjugated systems—for example, those at Nevada City, Grass Valley, and Ophir.

The Mother Lode (Fig. 180) is a belt of strong, closely spaced veins over 100 miles long and not much more than a mile wide. It parallels the axis of the range and the general trend of the formations. Many veins of this group strike about N. 25° W.

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[1] Lindgren, Waldemar: Gold-Silver Veins of Ophir, Calif. U. S. Geol. Survey *Fourteenth Ann. Rept.*, part 2, pp. 243–284, 1893.—The Gold-Quartz Veins of Nevada City and Grass Valley, Calif. U. S. Geol. Survey *Seventeenth Ann. Rept.* part 2, pp. 1–262, 1896.—Characteristic Features of the California Gold-Quartz Veins. Geol. Soc. America *Bull.*, vol. 6, pp. 221–240, 1896.

Ransome, F. L.: U. S. Geol. Survey *Geol. Atlas*, Mother Lode district, folio (No. 63), 1900.

Storms, W. H.: The Mother Lode Region, California. Cal. State Min. Bur. *Bull.* 18, 1900.

and dip about 60° E. Single deposits are developed for more than a mile along the strike.

As a rule the deposits are of low grade, the average tenor being about $4 a ton. Some mines exploit large bodies of ore that carry less than $3 a ton, but pockets of very rich ore have been found. The principal gangue minerals are quartz, carbonates, and albite. As a rule the gold is associated with sulphides, including pyrite, arsenopyrite, and pyrrhotite, with pyrite, chalcopyrite, and galena. Specularite, magnetite, tetrahedrite, molybdenite, telluride, and scheelite occur only locally. The sulphides constitute only a small percentage of the ore. By mechanical concentration deposits of very low grade are profitably worked. The silver content is small in most of the deposits.

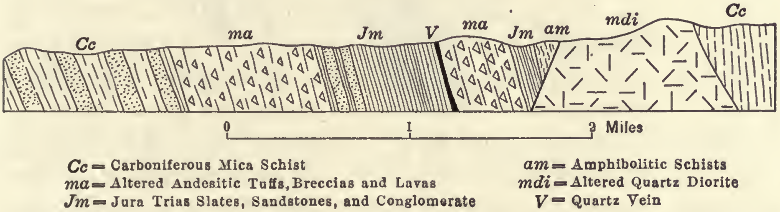

FIG. 180.—Cross-section of Mother Lode region, California. (*After Ransome, U. S. Geol. Survey.*)

There is no evidence that these deposits have been enriched by redeposition of gold; the outcrops are as rich as or richer than the ores in depth, and some of the deposits have been followed down the dip nearly a mile without notable change in value. Placers of enormous extent and value occur in this belt and have yielded more than half the gold derived from the deposits. At some places extensive stream placers are covered by Tertiary lavas. Doubtless many thousand feet of material has been eroded from these veins to supply the placer gold. They are nevertheless classed with veins formed at intermediate depths, for minerals indicating high temperature and pressure are only sparingly and locally developed. As a whole the group forms a transition type between the ores found in the deep-vein zone and those found at moderate depths. The remarkable persistence of the ore in depth points to ascending solutions as the agents of deposition, and the geographic relations of the deposits to intruding igneous rocks suggest a close genetic relation between the igneous rocks and the ore-depositing solutions.

PRODUCTION OF CERTAIN METALS IN CALIFORNIA, 1911–1915[a]

Year	Mines producing	Ore, (short tons)	Gold	Silver, (fine ounces)	Copper, (pounds)	Lead, (pounds)	Zinc, (pounds)	Total value
1911	1,181	2,797,261	$19,738,908	1,270,445	36,316,136	1,398,111	2,807,035	$25,174,677
1912	1,041	2,641,497	19,713,478	1,300,136	33,451,672	1,144,731	4,345,591	26,383,946
1913	796	2,495,958	20,406,958	1,378,399	34,575,007	3,514,342	1,057,485	26,812,487
1914	658	2,465,485	20,653,496	1,471,859	30,507,692	4,251,923	389,471	25,710,645
1915	608	3,002,779	22,442,296	1,678,756	40,751,625	4,579,245	13,094,032	32,263,844

[a] Yale, C. G.; U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 207, 1916.

Nevada City and Grass Valley, California.—The Nevada City and Grass Valley district,[1] which is one of the most steadily productive in California, includes metamorphosed Carboniferous sedimentary rocks, compressed into isoclines, and associated igneous rocks less intensely metamorphosed. Above these are slates with associated diabase and serpentine. These rocks are folded and metamorphosed but are not so intensely compressed as the Carboniferous. Intruded into them are great bodies of granodiorite, probably of early Cretaceous age. The ore deposits are strong veins, formed after the granodiorite intrusions. The gold content is somewhat higher than in ores of the Mother Lode. The minerals are quartz, chalcedony, magnetite, sericite, mariposite, pyrite, pyrrhotite, chalcopyrite, galena, zinc blende, scheelite, arsenopyrite, tetrahedrite, stephanite, and cinnabar.

Near the surface the upper part of a vein is generally decomposed, forming a mass of limonite and quartz. The decomposition does not as a rule extend more than 200 feet on the incline of a vein dipping 45°, or more than 150 feet below the surface. The surface ore is generally richer than the deeper ore, owing to the liberation of gold from the sulphides and the removal of substances other than gold. In this process silver also is partly removed. In some of the mines the lodes have been followed down the dip for over 3,000 feet. The unoxidized ore shows no gradual diminution of tenor in the pay shoots below the zone of surface decomposition. Valuable placer deposits were formed from these veins.

Juneau, Alaska.—The California gold belt extends northward into Oregon and Washington, and in much of the area of these

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[1] LINDGREN, WALDEMAR: The Gold-Quartz Veins of Nevada City and Grass Valley Districts, California. U. S. Geol. Survey *Seventeenth Ann. Rept.* part 2, pp. 1–262, 1896.

States it is probably below later lavas. Farther north rocks and deposits nearly related to those of the California gold belt are present in abundance. The gold deposits of the Juneau belt, Alaska,[1] as pointed out by Spencer, are probably similar in age and origin to the California veins. The Treadwell group of mines, on Douglas Island, exploits the most productive lode deposits in Alaska. The district has been producing gold almost continually since 1880. Although the ore as mined carries only about $2 a ton, operations are highly profitable owing to the low cost of mining and milling. On the mainland, across the narrow Gastineau Channel, a short distance from the Treadwell mines, the Alaska Gold Mines Co. and the Alaska Juneau Co. are mining great low-grade deposits on a scale comparable to operations in the disseminated ("porphyry") copper deposits of the Southwest.

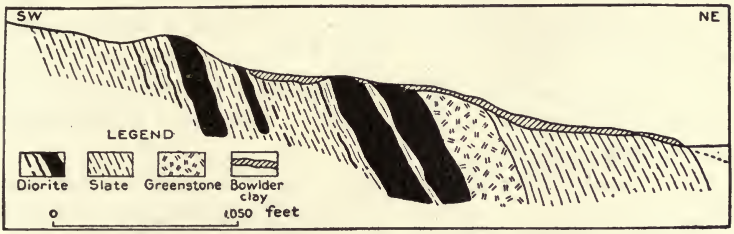

Fig. 181.—Cross-section through Alaska Treadwell mine and north side of Douglas Island, Alaska. (*After Spencer, U. S. Geol. Survey.*)

The rocks of this region consist of Paleozoic greenstones, slates, and schists, all of which are changed by pressure and crop out as parallel belts trending northwest. The dip is in general northeast. The Paleozoic rocks are intruded by gabbro, diorite, and diorite porphyry.

At the Treadwell mines (Fig. 181) great dikes of albite diorite intrude the greenstones and schist, and the shattered diorite has been extensively replaced by mineralizing solutions and cemented by low-grade gold ore. Hydrothermal alteration is attended by the development of albite and calcite. The minerals include also quartz, rutile, mariposite, chlorite, epidote, siderite, pyrite,

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[1] Spencer, A. C.: The Juneau Gold Belt, Alaska. U. S. Geol. Survey *Bull.* 287, 1906.

Hershey, O. H.: Geology of the Treadwell Mines. *Min. and Sci. Press*, vol. 102, pp. 296–300, 334–335, 1911. Also in Bain, H. F., and others, "Types of Ore Deposits," pp. 157–171, San Francisco, 1911.

pyrrhotite, magnetite, chalcopyrite, and molybdenite. No manganese minerals are reported.

The ore bodies of Douglas Island are the albite diorite dikes seamed and impregnated with pyrite, gold, and other minerals. They are locally more than 200 feet wide and extend downward to great depths, 2,000 feet or more. According to Spencer the ore shows no progressive change in appearance or value with increasing depth.

Cripple Creek, Colo.—The Cripple Creek district, Colorado,[1] is about 10,000 feet above sea level, in the high country southwest of Pikes Peak. It has produced over $250,000,000 in gold. The ore, which generally runs from $12 to $20 a ton, is roasted and treated by cyanidation. Some lots much richer are smelted. In 1915 Cripple Creek produced 948,082 tons of ore containing $13,683,494 in gold. A little silver is recovered, with insignificant quantities of other metals.

The oldest rocks of the region are pre-Cambrian granite, gneiss, and schist. A volcanic neck of Tertiary age 2 or 3 miles in diameter breaks through the pre-Cambrian rocks (page 213). This neck is the core of a volcano through which lavas were thrown out upon the ancient rocks, but most of the lavas have been removed by erosion. The volcanic neck is composed mainly of tuffs and breccias of latite-phonolite which are cut by dikes and stocks of latite-phonolite, syenite, and other alkali-rich intrusives. Phonolite and basic dikes cut the Tertiary rocks and the pre-Cambrian rocks near the volcanic center. The ore deposits (Fig. 182) are veins that were formed soon after the basic dikes. Many of them lie along the walls of the dikes and, like the dikes, are rudely radial about the volcanic neck. The veins were formed by filling small openings along fissures and sheeted zones and subordinately by replacement. Some irregular replacement deposits occur in shattered granite. The fissures are believed by Lindgren and Ransome to have been produced by stresses attending the settling of the volcanic mass.

Hydrothermal action was not particularly intense although it was widespread, especially in the porous volcanic breccia.

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[1] Penrose, R. A. F.: Mining Geology of the Cripple Creek District, Colorado. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 2, p. 123, 1895.

Lindgren, Waldemar, and Ransome, F. L.: Geology and Gold Deposits of the Cripple Creek District, Colorado. U. S. Geol. Survey *Prof. Paper* 54, pp. 167–168, 1906.

Dark silicates were changed to pyrite, carbonates, and fluorite, and feldspars and feldspathoids were changed to sericite and adularia. Calaverite is the chief primary constituent of the ores; native gold is rarely present in the unoxidized ores. Pyrite is widely distributed; tetrahedrite, stibnite, sphalerite, and molybdenite are sparingly present. The gangue is made up of quartz, fluorite, adularia, carbonates (including rhodochrosite), some sulphates, and other minerals. Some of the deposits were workable at the surface, but the placers formed are of relatively little value.

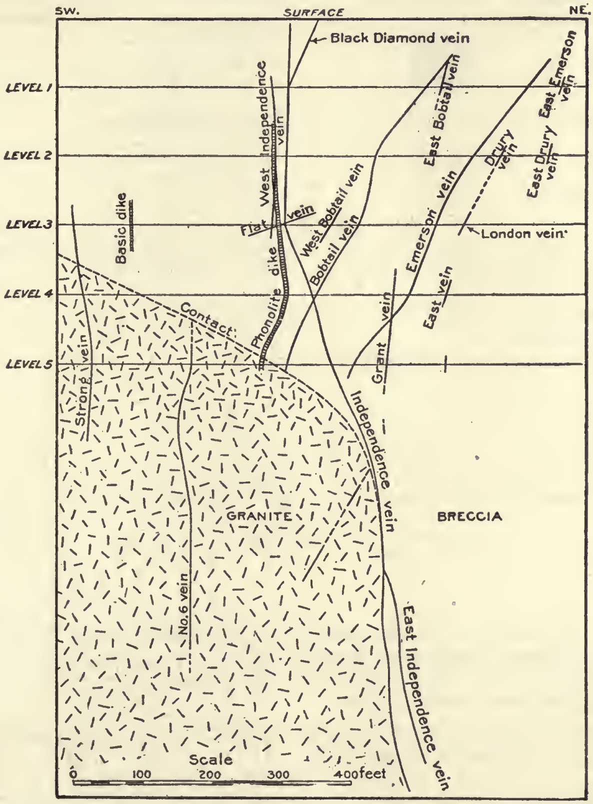

FIG. 182.—Section through Stratton's Independence mine, Cripple Creek, Colorado, showing relation of veins to granite-breccia contact. (*After Lindgren and Ransome, U. S. Geol. Survey.*)

In general, the lower part of the zone of oxidation is above water level and is usually less than 200 feet deep. Exploration is extensive to depths of 1,500 feet below the surface. Whether a slight enrichment of gold has taken place in the superficial zone is not easy to demonstrate. The oxidized zone as a whole is probably somewhat richer than the corresponding telluride zone. The enrichment in this zone, however, may have resulted from the removal of valueless constituents of the primary ore.

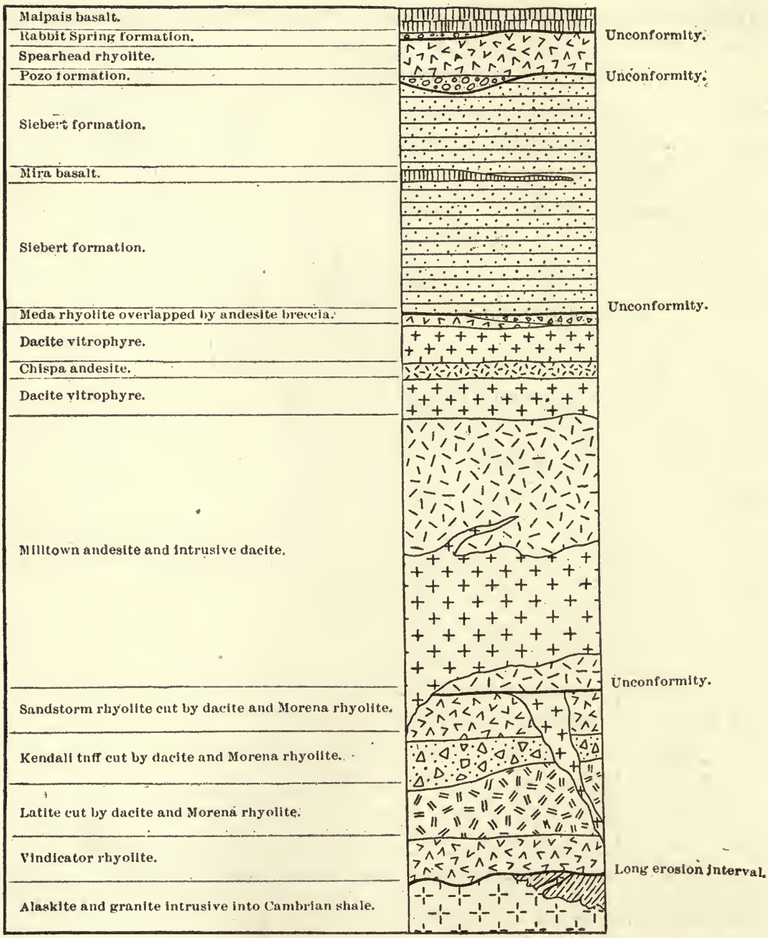

FIG. 183.—Generalized columnar section of the rocks of the Goldfield district, Nevada. (*After Ransome, U. S. Geol. Survey.*)

If gold was dissolved in the Cripple Creek deposits it was precipitated again at practically the same horizon, for in these deposits the zone in which solution usually takes place is rich. The ground is open, providing paths for downward-circulating waters, but although the ore-bearing complex is very pervious to water it is surrounded by impervious rocks. After the volcanic rocks had been drained in mining the flow of water was comparatively small. Lindgren and Ransome have compared the volcanic complex to a "sponge in a cup." As shown by them,

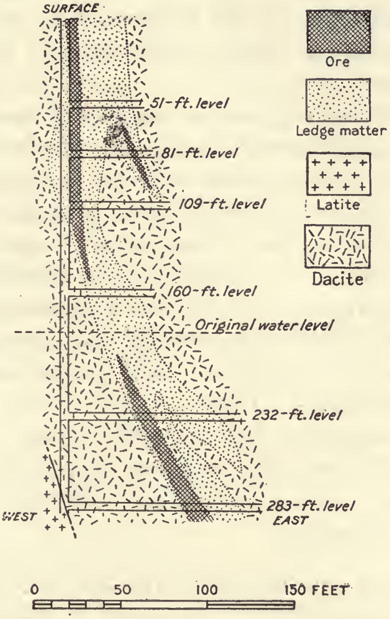

FIG. 184.—Cross-section of January mine, Goldfield, Nevada. (*After Ransome, U. S. Geol. Survey.*)

the conditions were unfavorable for the circulation of atmospheric water.

Interesting experiments bearing on the downward migration of gold at Cripple Creek have been made by Nishihara,[1] who showed that alkali-rich minerals such as nepheline and leucite reduce the acidity of solutions very rapidly.

Goldfield, Nev.—The Goldfield district, Nevada,[2] is essen-

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[1] NISHIHARA, G. S.: The Rate of Reduction of Acidity of Descending Waters by Certain Ore and Gangue Minerals and Its Bearing upon Secondary Sulphide Enrichment. *Econ. Geol.*, vol. 9, pp. 743–757, 1914.

[2] RANSOME, F. L.: The Geology and Ore Deposits of Goldfield, Nev. U. S. Geol. Survey *Prof. Paper* 66, p. 27, 1909.

tially a low domical uplift of Tertiary lavas and lake sediments resting upon ancient granitic and metamorphosed sedimentary rocks. Erosion of the flat dome has exposed the pre-Tertiary rocks at several places, and these are surrounded by wide zones of younger formations. Some of the later lavas were erupted after the dome had been elevated and truncated. The Tertiary rocks are mainly volcanic, as is indicated by Fig. 183. The dacite occupies a considerable area east of Goldfield and is the principal country rock of the larger mines. Some rich shoots were found also in the Milltown andesite, in latite, and in the Sandstorm rhyolite.

The region of the deposits is complexly fissured, but faults are few and of small throw, and the Tertiary beds are not steeply tilted. The fracture system is very irregular. The rocks, especially the dacite, have undergone extensive hydrothermal alteration, attended by the development of much alunite, kaolin, quartz, and pyrite. The deposits are associated with iron-stained silicified craggy outcrops, but a great many of these outcrops are barren. The deposits (Fig. 184) are related to fissures and were formed by replacement; only a small part of the ore has actually filled fractures. Ransome terms them "ledges," using the term in a sense less definite than "veins" to designate the masses of silicified or otherwise altered rock in which the ore bodies are found. The workable ore bodies are very irregularly distributed in the ledges.

METAL PRODUCTION OF GOLDFIELD DISTRICT, NEVADA, 1914–1915[a]

Year	Ore (short tons)	Gold	Silver (fine ounces)	Copper (pounds)	Lead (pounds)	Total value
1914	367,166	$4,705,169	129,830	1,069,021	4,018	$4,919,302
1915	418,935	4,389,385	165,306	1,679,423	....	4,767,094
Total, 1914–1915	....	75,700,937	998,748	4,819,203	23,662	77,022,591

[a] HEIKES, V. C.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 631, 1916.

The sulphide ores are mineralogically complex and are accompanied by minerals containing copper, silver, antimony, arsenic, bismuth, and tellurium. In some ores the gold occurs free, in fine particles, so closely crowded in the flinty quartz gangue as to form yellow bands. Associated minerals are pyrite, marcasite, bismuthinite, famatinite (Cu_3SbS_4), and goldfieldite (a cupric sulphantimonite). A concentric crustification is characteristic of the richest ores, fragments of silicified, alunitized, and pyritized rock being covered with shells of gold and sulphides. Near the surface oxidized ores predominate. Among the minerals of this ore are kaolin, alunite, gypsum, barite, alum, and iron oxides. Silver halides are not common, and manganese compounds are practically unknown. No valuable placers have been formed in this region.

The deposits, according to Ransome, are probably late Miocene or early Pliocene. As the Siebert tuffs are alunitized and are not known to contain fragments of alunitized dacite, and as the Pozo formation contains fragments of alunitized dacite, the metallization is probably post-Siebert and pre-Pozo (see Fig. 183).

The ledges were probably deposited near the Tertiary surface. They are believed to have been formed by hot ascending solutions from a deep source, which mingled with descending sulphate water that contained oxygen derived from the air. Although some erosion has taken place since the ores were deposited, the effects of enrichment are believed to be subordinate.

CHAPTER XXV

SILVER

MINERAL COMPOSITION OF SILVER DEPOSITS

Mineral	Percentage of silver	Composition
Silver	100.0	Ag.
Cerargyrite	75.3	AgCl
Bromyrite	57.4	AgBr.
Embolite	65.1	Ag(Cl, Br).
Iodyrite	46.0	AgI.
Argentite	87.1	Ag_2S.
Pyrargyrite	59.9	Ag_3SbS_3 or $3Ag_2S.Sb_2S_3$.
Proustite	65.4	Ag_3AsS_3 or $3Ag_2S.As_2S_3$.
Stephanite	68.5	Ag_5SbS_4 or $5Ag_2S.Sb_2S_3$.
Polybasite	75.6	Ag_9SbS_6 or $9Ag_2S.Sb_2S_3$.
Pearceite	78.4	Ag_9AsS_6 or $9Ag_2S.As_2S_3$.
Tetrahedrite	Variable	$4Cu_2S.Sb_2S_3$ or $4(Cu_2Ag_2)S.Sb_2S_3$.
Tennantite	Variable	$4Cu_2S.As_2S_3$ or $4(Cu_2Ag_2)S.As_2S_3$.
Tellurides.		

Unlike gold, silver forms many stable compounds. Of these only a few, the more common ores, are mentioned above. The silver ores are generally more complex than those of gold and more difficult to treat.

Silver in many deposits occurs in an undetermined state intergrown with other minerals. Thus galena is commonly argentiferous, and sphalerite, pyrite, or other sulphides may carry enough silver to make it the principal consideration in the ore. Nearly all copper deposits carry some silver, and in smelting much of it is recovered. The muds that are obtained from the electrolytic refining of copper are smelted for silver and gold. Nearly all the lead ores of the West carry notable amounts of silver, and gold ores are very commonly argentiferous.

The gangue minerals of silver ores are similar to those of copper and gold ores. Quartz, carbonates, and sericite are among the common minerals in deposits of both metals.

The primary deposits of silver are principally veins and nearly related deposits. Workable deposits formed by magmatic segregation or as pegmatite veins are practically wanting, and silver is relatively rare or subordinate in most contact-metamorphic deposits and veins of the deep zone. Silver deposits are formed mainly at moderate and shallow depths and are characteristically developed in the central belt mentioned in the discussion of gold deposits (page 404) and in the middle and late Tertiary group. Silver is deposited by cold solutions in a few of its primary deposits, as in the Red Beds of Colorado, Arizona, and New Mexico, in which it is associated with copper sulphides. Syngenetic deposits of silver ores are practically unknown in North America.

AGE OF SILVER DEPOSITS IN NORTH AMERICA

The silver ores of North America range in age from pre-Cambrian to late Tertiary. Cobalt, Ontario, the most productive silver district on the continent, is in an area of pre-Cambrian rocks, and probably the ores are pre-Cambrian, but they appear to have been formed at moderate depths. The copper deposits of Keweenaw Peninsula, Michigan, carry some silver. Silver is generally not abundant in early Cretaceous deposits, such as the California gold lodes. In late Cretaceous and early Tertiary time silver was deposited in considerable amounts in Montana (Butte, Philipsburg, Elkhorn), in Colorado (Leadville), in Utah (Park City) and in many other districts of the so-called central belt. Silver was deposited in largest amounts in middle and late Tertiary time, especially in the Basin province, which includes Nevada and parts of the adjoining States. During this period the great deposits of the Comstock lode, Tuscarora, Tonopah, and many other districts in the United States and in Mexico were formed.

ENRICHMENT

Silver is dissolved in dilute sulphuric acid and is precipitated in a reducing environment by metallic sulphides or by hydrogen sulphide. Silver chloride is comparatively insoluble. Although ferrous sulphate and copper sulphate remain dissolved even in solutions of high concentration, ferrous sulphate precipitates metallic silver from a dilute solution of silver sulphate according to the reaction $Ag_2SO_4 + 2FeSO_4 = 2Ag + Fe_2(SO_4)_3$.

Silver sulphate, which is somewhat soluble, is formed by the action of concentrated sulphuric acid on silver. According to Cooke,[1] silver sulphide is only slightly soluble in very dilute sul-

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[1] Cooke, H. C.: The Secondary Enrichment of Silver Ores. *Jour. Geol.*, vol. 21, p. 17, 1913.

phuric acid, but if a little ferric sulphate is added to the solution the solubility of the sulphide is considerably increased. Silver sulphate is easily attacked by many minerals, the native metal being deposited.

Notwithstanding the low solubility of the silver halides, it seldom happens that all the silver dissolved in the upper parts of an argentiferous deposit is fixed as halides. The formation of the chloride near the surface does not entirely inhibit the downward migration of silver. The secondary silver sulphides are numerous and in some veins abundant.

Silver is readily precipitated as argentite below the zone of oxidation on account of the low solubility of its sulphide. It stands near the end of the Schuermann series, being preceded only by mercury, and accordingly it should replace most other metals in sulphide combinations. With silver sulphate (Ag_2SO_4) hydrogen sulphide, which is generated by acid reacting upon zinc blende, galena, or other sulphides, gives argentite. The reaction is

$$Ag_2SO_4 + H_2S = Ag_2S + H_2SO_4.$$

If the reaction is with galena, or if lead sulphide is precipitated simultaneously with argentite, argentiferous galena may be formed. If arsenic and antimony are present in solution, the complex sulphosalts of these metals may be formed.

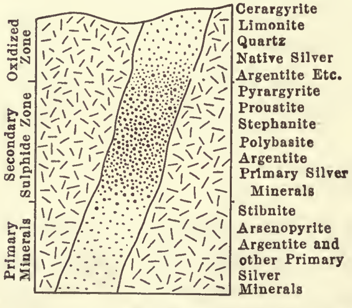

FIG. 185.—Ideal section showing distribution of minerals in a silver deposit that has been superficially altered.

In many silver deposits secondary pyrargyrite, proustite, stephanite, and polybasite are the most valuable minerals. These minerals are probably formed only in the lower part of the secondary sulphide zone (Fig. 185), where alkaline conditions generally prevail (see Fig. 66, page 134). If stibnite is treated with a dilute alkaline solution such as sodium carbonate or sodium hydroxide, sodium-antimony sulphide is formed. With silver sulphate the salt forms a compound having the composition of stephanite, $(Ag_2S)_5Sb_2S_3$.

$$(Na_2S)_5Sb_2S_3 + 5Ag_2SO_4 = 5Na_2SO_4 + (Ag_2S)_5.Sb_2S_3$$

It has been shown that there is below the surface a zone of alkaline waters where oxygen is excluded and where underground waters react for long periods on alkaline rocks. Above the alkaline zone the waters are acid. After a series of heavy rains or during a wet period the water level is elevated, and the acid waters descend rapidly on account of increased pressure of the water above the acid zone. The descending acid waters will mingle with the alkaline waters. Acid waters containing silver sulphate, reacting with alkaline waters containing sodium-antimony sulphide, can form stephanite and pyrargyrite, as has been shown by Grout[1] and by Ravicz.[2]

In many deposits containing silver chloride, native silver, silver sulphide, and the arsenic and antimony sulphosalts, these minerals occur at fairly well defined horizons. The chloride is most abundantly developed above the argentite ore; the antimony and arsenic sulphosalts are found with and below the argentite; the native metal is found with the chloride, and, overlapping the zone of chloride ores, it extends downward with argentite. In sulphide deposits of silver and copper the richer silver ores are generally nearer the surface than the richer copper ores. Some of the great copper lodes of Butte, Mont., were worked for silver to depths of 200 to 400 feet below the surface, where the deposits changed to rich copper ore. Like gold, silver would be driven from sulphate solutions in an environment where chalcocite forms.

Native silver is a primary mineral in some deposits, as in the zeolitic copper ores of Lake Superior, but in sulphide deposits it is generally or invariably secondary. In some districts it is among the most valuable ore minerals. It commonly occurs as thin flakes or as sheets plastered on the older minerals or as veinlets filling cracks in the ore, and presumably it has been formed at many places through the reduction of silver sulphides or other silver-bearing minerals.

Cerargyrite is unknown as a primary constituent of ores deposited by ascending hot waters but is frequently developed by weathering, at or near the outcrops of silver-bearing sulphide

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[1] Grout, F. F.: On the Behavior of Cold Acid Sulphate Solutions of Copper, Silver, and Gold with Alkaline Extracts of Metallic Sulphides. *Econ. Geol.*, vol. 8, pp. 407–433, 1913.

[2] Ravicz, L. G.: Experiments in the Enrichment of Silver Ores. *Econ. Geol.*, vol. 10, pp. 378–384, 1915.

lodes. At many places, even where the primary sulphide ores are not profitable, the superficial chloride ores may be very rich. The chloride ores generally pass into the sulphides below, and the bottom of the zone of ore carrying horn silver is generally above the bottom of the zone of secondary silver sulphides.

Argentite is one of the commonest secondary silver minerals, but it occurs also as a primary mineral. If sulphuric acid in its descent encounters a soluble sulphide like zinc blende, hydrogen sulphide and zinc sulphate are formed. The hydrogen sulphide would precipitate silver sulphide from a solution containing Ag_2SO_4. Argentite could be precipitated in any of the following reactions:

$$H_2S + Ag_2SO_4 = H_2SO_4 + Ag_2S$$
$$ZnS + Ag_2SO_4 = ZnSO_4 + Ag_2S$$
$$PbS + Ag_2SO_4 = PbSO_4 + Ag_2S$$

Pyrargyrite (dark ruby silver), is probably the most abundant secondary silver mineral in a large number of silver mines in the United States. It is confined to epigenetic deposits and occurs in many deposits of early and middle Tertiary age in the American Cordillera. It is not known as a primary mineral of contact-metamorphic deposits and veins of the deep zone. In some mines ruby silver is found at considerable depths, however, possibly below the zone of secondary alteration.

Proustite (light ruby silver) is similar to pyrargyrite in its occurrences and is generally secondary.

Stephanite is common in some districts. It generally accompanies ruby silver and polybasite, and in places it occurs, like them, in cracks cutting the primary ore.

Polybasite is commonly a secondary mineral. It occurs in several mining districts in cracks cutting the primary ore and in the main is related to the present surface.

Pearceite is less common than the corresponding antimony salt, polybasite. It is generally secondary.

Freibergite, the argentiferous variety of tetrahedrite, is an important source of silver in many deposits. It is primary in most districts but is probably secondary in some.

Tennantite has the same range of occurrence as the corresponding antimony sulphide, tetrahedrite.

SILVER-BEARING DISTRICTS

Cobalt, Ont.—Cobalt,[1] in the Nipissing district, northern Ontario, is at present the most productive silver-bearing district in North America. The ore is very rich and, shipments carrying 1,000 ounces or more to the ton are not uncommon. Much of the ore is sent directly to smelters, but in recent years some of the larger mining companies have built mills, and the lower-grade material is concentrated.

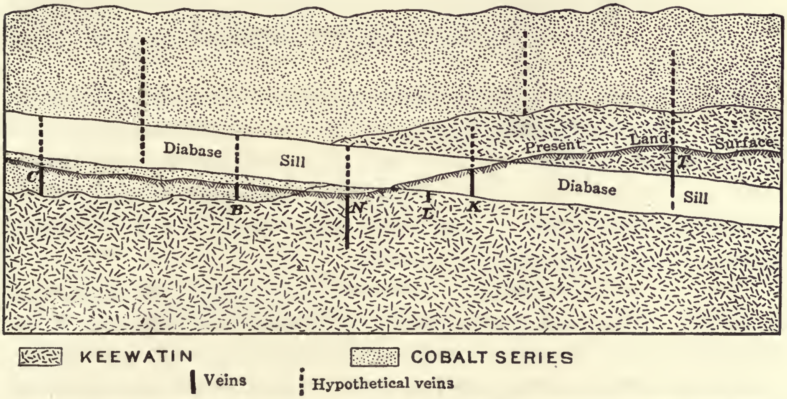

FIG. 186.—Generalized vertical section through the productive part of the cobalt area, Ontario.

The section shows the relations of the Nipissing diabase sill to the Keewatin and Cobalt series and to the veins. The eroded surface is restored in the section. The sill is less regular than the illustration shows it to be. *B* and *C* represent a large number of veins that are in the fragmental rocks (Cobalt series), in the lower or footwall of the eroded sill. *N* represents a type of vein, such as No. 26 on the Nipissing, in the Keewatin below the eroded sill, and *L* a type such as one under Peterson lake, in the Keewatin footwall, but not extending upward into the sill; *K*, a vein in the sill itself, such as No. 3 on the Kerr Lake property: *T*, a vein, such as that on the Temiskaming or Beaver properties, in the Keewatin hanging wall and extending downward into the sill. (*After Miller.*)

Cobalt is on the great ancient peneplain which extends over much of Ontario and the surrounding region. The country is hilly, but the relief is not great. The recent glaciation is clearly evident, but drift is generally thin or absent.

The basement rocks are the Keewatin series, a complex of metamorphosed basic igneous rocks, usually known as greenstones, which includes also some rock of sedimentary origin. The eroded surface of the Keewatin is overlain by Huronian conglomerates, graywacke, and other metamorphosed sedi-

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[1] MILLER, W. G.: The Cobalt-Nickel Arsenides and Silver Deposits of Temiskaming, 3d ed. Ontario Bur. Mines *Rept.*, vol. 16, part 2, 1908:—4th ed. *Idem.*, vol. 19, part 2, 1913.

mentary rocks. A quartz diabase sill some 500 feet thick was intruded into both Huronian and Keewatin rocks. This dips about 17°S.

The deposits are short, narrow veins, very numerous and rich. They are found in the Huronian, in the diabase, and in the Keewatin, but the more productive deposits are in the Huronian near the diabase sill, or they were below the foot wall of the sill before the sill was eroded (Fig. 186). The deposits are probably genetically related to the diabase, and the fractures have been assumed to represent cooling cracks formed in connection with the intrusion. Post-mineral fracturing and faulting have taken place extensively.

The principal sulphides of earlier age include smaltite, cobaltite, chloanthite, and bismuth sulphide, with some arsenopyrite and tetrahedrite. Pyrite, galena, and sphalerite are present in the wall rock near the vein. The silver occurs as native metal, proustite, pyrargyrite, dyscrasite, and argentite. The gangue minerals include calcite and quartz.

The zone of oxidation is exceedingly shallow or altogether lacking, but certain exceptionally rich superficial deposits, a few feet thick, are directly connected with the zone of weathering. This is called the "nugget horizon," and in it the smaltite and cobaltite have been largely altered to secondary minerals or leached out. In this zone erythrite and annabergite are characteristic minerals.

Extending downward 200 or 300 feet or more below the surface are rich silver minerals, largely in veinlets in earlier sulphides. The minerals of the veinlets include native silver, argentite, and calcite. The change from rich to low-grade ore is very abrupt both in depth and on the strike. Some writers[1] have attributed these richer silver ores to processes of sulphide enrichment, but Miller is inclined to the belief that this feature of the genesis has been too much emphasized. Notwithstanding its late age and

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[1] Van Hise, C. R.: The Ore Deposits of the Cobalt District, Ontario. Canadian Min. Inst. *Jour.*, vol. 10, pp. 43–53, 1907.

Emmons, S. F.: Cobalt District, Ontario, in, Bain, H. F., and others: "Types of Ore Deposits," pp. 140–156, San Francisco, 1911.

Campbell, W., and Knight, C. W.: Microscopic Examination of the Cobalt-Nickel Arsenides and Silver Deposits of Temiskaming. *Econ. Geol.*, vol. 1, p. 757, 1906.

Hore, R. E.: Geology of the Cobalt District. Am. Inst. Min. Eng. *Trans.*, vol. 42, p. 480, 1911.

its occurrence in cracks of older shattered remnants, he believes that much of the native silver is primary.

Eureka, Nev.—The Eureka district, in Eureka County, eastern Nevada, from 1869 to 1883 yielded about $60,000,000 in silver and gold and 225,000 tons of lead. After that the production declined greatly, but in late years considerable ferruginous gold ore has been shipped to Utah smelters, where it is in demand on account of its fluxing properties. Most of the Eureka ore, however, was beneficiated in lead smelteries at Eureka. In 1915 it produced 109,320 tons of ore containing $500,040 in gold, silver, lead, zinc, and copper.

The district[1] is an area of Paleozoic quartzites, limestones, and shales, which were intruded, probably in late Mesozoic time, by granite, granite porphyry, and quartz porphyry. Later, probably in the Tertiary period, the sedimentary rocks were intruded by great igneous bodies of andesitic composition and covered in places by rhyolite and basalt. The beds are thrown into open folds, and the dominant structure is that of a fault mosaic, the principal faults being of the normal type.

The ores occur in Paleozoic sedimentary rocks. The ore bodies have been formed chiefly by the replacement of fractured limestones[2] and include lodes, stocks, and bedding-plane deposits. Near the deposits great masses of limestone are impregnated with magnetite.

The larger ore bodies are capped by caves developed by solution, and the fall of rock into openings has caused further fissuring. Subsequently the metals have in many places been redistributed by underground waters. The ore above the water level is composed principally of galena, anglesite, cerusite, mimetite, and wulfenite, with much limonite, quartz, and calcite. It carries also considerable gold and silver and some zinc. The ore below the water level is composed chiefly of pyrite, arsenopyrite, galena, zinc blende, and other sulphides, with silver and gold. At some places altered ore is found below the water level, and Curtis supposed that the water level had been recently elevated. Large bodies of low-grade limonitic gold ore have been mined in the shattered and altered limestones that surround the old silver stopes.

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[1] Hague, Arnold: Geology of the Eureka District, Nevada. U. S. Geol. Survey *Mon.* 20, 1892.

[2] Curtis, J. S.: Silver-Lead Deposits of Eureka, Nev. U. S. Geol. Survey *Mon.* 7, 1884.

Boulder-Leadville Belt, Colorado.—Lying 30 or 40 miles west of Denver, Colo. and extending from Boulder southwest to Leadville, a distance of about 80 miles (Fig. 187) is one of the most richly mineralized belts in North America. This belt is occupied by pre-Cambrian schists, gneisses, granites, and other igneous rocks overlain by Paleozoic and Mesozoic sedimentary rocks. It contains many porphyry dikes, sills, and stocks, which are believed to be of late Cretaceous or early Tertiary age. Closely associated with the intrusive rocks and probably of about the same age are numerous deposits containing silver, gold, lead, and other metals. In the igneous rocks and schists the principal deposits are normal veins. In the limestones irregular replacement and bedding-plane deposits predominate. Some subdistricts exhibit parallel coördinated vein systems.

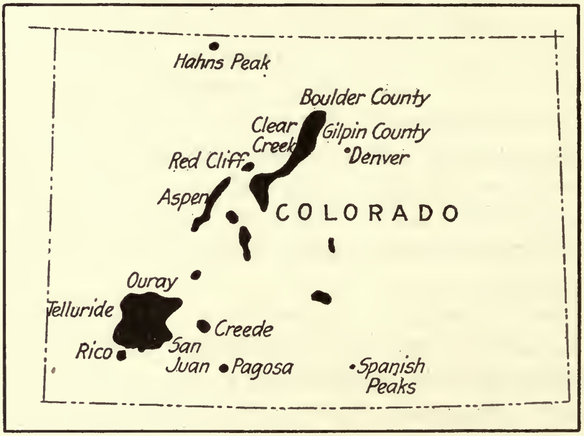

FIG. 187.—Sketch showing metallized areas in Colorado. (*After Spurr and Garrey, U. S. Geol. Survey.*)

The ores vary from place to place but normally contain a fairly high proportion of sulphides, including pyrite, sphalerite, galena, chalcopyrite, and tetrahedrite. Normally the gangue is quartz, but some deposits contain also carbonates and barite. In the wall rock near the veins sericite and carbonates occur. There is very little contact metamorphism near the intruding rocks, and no andradite-amphibole border zones are developed. The deposits have been formed mainly at moderate depths, probably between 1 and 2 miles below the surface; those formed at the greater depths are most abundant in the southwestern part of the area.

Although the deposits occur in rocks of varied composition and character, no relation between their composition and that of the containing rocks is recognized. Ores of similar composition may be found in sedimentary, metamorphic, and igneous rocks. Differences in vein composition appear to be related rather to differences in the character of the associated intruding rocks. In the Georgetown quadrangle[1] the areas containing veins coincide with areas containing porphyry dikes. In the Georgetown district, characterized by argentiferous galena-blende veins, the dikes consist of alaskite porphyry, granite porphyry, quartz monzonite porphyry, and dacite. In the Idaho Springs district, characterized by pyritic gold veins, the dikes are bostonite, alaskitic quartz monzonite, biotite latite, and alkali syenite. The dikes near Georgetown belong to the early Tertiary monzonitic magma; the rocks of the Idaho Springs district are referable to an alkaline magma. Similarly, there are two classes of ore deposits in the quadrangle, the deposition of which has in general followed the eruption of the different groups of magmas.

Many deposits of this belt have been enriched by superficial alteration, but commonly the veins become unprofitable a few hundred feet below the surface. Some of the districts of this belt are discussed in the following paragraphs.

Breckenridge.—The oldest rocks in the Breckenridge region[2] are pre-Cambrian granites, gneisses, and schists. The oldest sedimentary rocks, which rest directly on the pre-Cambrian, are red sandstones and shales, supposed to be of Triassic or Permian age. Apparently conformable above them is the Dakota quartzite, with some gray shale, which is overlain by a thick formation of Upper Cretaceous shales. The sediments and the pre-Cambrian rocks are intruded by monzonitic porphyries, which occur mainly as sills.

The ore deposits include veins of a zinc-lead-silver-gold series, stockworks and veins of a gold-silver-lead series, and the gold veins of Farncomb Hill. Gold placers also are present.

In the Wellington veins, which belong to the zinc-lead-silver-

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[1] SPURR, J. E., and GARREY, G. H.: Economic Geology of the Georgetown Quadrangle, Colorado. U. S. Geol. Survey *Prof. Paper* 63, p. 157, 1908.

[2] RANSOME, F. L.: Geology and Ore Deposits of the Breckenridge District, Colorado. U. S. Geol. Survey *Prof. Paper* 75, pp. 25–26, 1911.

gold series, the filling consists of sulphides, mainly galena, sphalerite, and pyrite, without much quartz.

A notable feature of the oxidized ores is their general high content of lead and silver as compared with the sulphides beneath. In some mines the deep ores are not profitable. Here and there the oxidized ores show also a noteworthy concentration of gold, where the sulphide ores below contain only small quantities.

Silver Plume.—The Silver Plume district,[1] near Georgetown, is an area of pre-Cambrian gneisses, schists, granites, and diorites intruded by early Tertiary or late Cretaceous porphyry dikes. These trend northeast and southeast and cross the schistosity at high angles. The ore deposits are veins, which also strike northeast and southeast. Many of them follow contacts of porphyry dikes. The veins contain silver and lead without much gold. The principal minerals are pyrite, sphalerite, and galena, with some polybasite, pyrargyrite, and argentite. Sulphide enrichment has enhanced the value of the ore near the surface.

Idaho Springs.[2]—The Idaho Springs district is mainly in the northeast corner of the Georgetown quadrangle, extending beyond its limits. The rocks are principally schists of the Idaho Springs formation, belonging to the pre-Cambrian complex that is present at Silver Plume. These are intruded by porphyry dikes. Both schists and dikes are cut by veins, many of which parallel the dikes. Some of the veins carry gold, others silver, still others both metals. Some of the ore shoots are located at junctions of veins. By superficial alteration many of the deposits are enriched near the surface. Gold placers have been formed.

Gilpin County.—Gilpin County,[3] northeast of Georgetown, is one of the most steadily productive regions in Colorado. The country rock is a pre-Cambrian complex cut by porphyry dikes. The ore deposits of Gilpin County and adjacent areas include gold-silver ores, uranium ores, and tungsten ores. The tungsten ores are prominent also in the adjoining Boulder County. Most of the ore bodies occupy zones of fracturing and minor faulting.

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[1] Spurr, J. E., and Garrey, G. H.: Economic Geology of the Georgetown Quadrangle, Colorado. U. S. Geol. Survey *Prof. Paper* 63, pp. 176–243, 1908.

[2] Spurr, J. E., and Garrey, G. H.: *Op. cit.*, pp. 314–382.

[3] Bastin, E. S., and Hill, J. M.: Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder Counties, Colorado. U. S. Geol. Survey *Prof. Paper* 94, pp. 190–280, 1917.

Leadville.—Leadville[1] stands about 10,000 feet above sea level, on a high terrace at the foot of a spur of the Mosquito Range. The district is one of the most productive in the West and has yielded large quantities of lead and silver, considerable gold, zinc, and copper, and some iron, manganese, and bismuth. In 1915 it produced 470,808 tons of ore which yielded $2,003,866 in gold, 2,389,371 ounces of silver, 1,782,235 pounds of copper, 20,808,407 pounds of lead, and 72,424,873 pounds of zinc, with a total value of $13,485,847.

The normal sequence of rocks in the district from the top down is as follows:

Local name	Age	Character	Average thickness (feet)
Weber shales	Lower Carboniferous	Shales and grit	0 to 2,500
White porphyry	Pre-Cretaceous	White rhyolite porphyry	800
Blue limestone	Lower Carboniferous	Blue-gray dolomite	200
Gray porphyry	Pre-Cretaceous	Gray monzonite porphyry	50
Parting quartzite	Devonian	Coarse quartzite	30
White limestone	Silurian	Drab siliceous dolomitic limestone.	160
Lower quartzite	Cambrian.	Mostly white quartzite	160
Granite	Basement complex or pre-Cambrian.	Granite and gneiss	

The porphyries are intruded mainly as sheets, but locally they cut the sedimentary rocks. They range from a few feet to several hundred feet in thickness. They are generally separated by the blue-gray dolomite, as indicated in the table, but at several places they are in contact with each other. At some places there is more than one sheet of the gray porphyry. Over much of the area erosion has removed the top of the white porphyry. The

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[1] Emmons, S. F.: Geology and Mining Industry of Leadville, Colo. U. S. Geol. Survey *Mon.* 12, 1886.

Emmons, S. F., and Irving, J. D.: The Downtown District of Leadville, Colo. U. S. Geol. Survey *Bull.* 320, 1907.

Argall, Philip: The Zinc Carbonate Ores of Leadville: Min. Mag.; vol. 10, pp. 282–288, 1914.

Ricketts, L. D.: "The Ores of Leadville," Princeton, 1883.

Blow, A. A.: The Geology and Ore Deposits of Iron Hill, Leadville, Colo. Am. Inst. Min. Eng. *Trans.*, vol. 18, pp. 145–181, 1890.

Butler, G. M.: Some Recent Developments at Leadville. *Econ. Geol.*, vol. 7, pp. 315–323, 1912; vol. 8, pp. 1–18, 1913.

Boehmer, Max: The Genesis of Leadville Ore Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 41, pp. 162–165, 1911.

most valuable deposits are found in Carboniferous limestone at or near its contact with an overlying porphyry. Thus the ore bodies constitute sheets, the upper surfaces of which, being formed by the bases of the porphyry bodies are comparatively regular, while the lower surfaces are ill defined and irregular, there being a gradual transition from ore to limestone. The ore extends to varying depths below the surface, occupying in places the entire thickness of the Leadville ("Blue") limestone. Other deposits include, however, steeply dipping veins, some of them in fault fissures, and irregular masses or sheets in limestone near the "Gray" or other porphyries (Fig. 188).

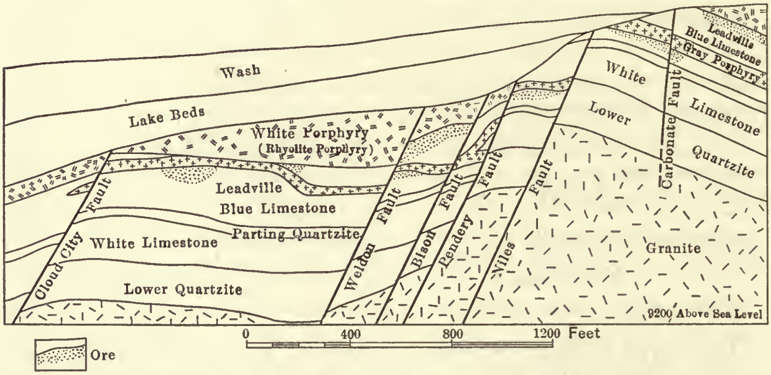

FIG. 188.—Geologic section of the Downtown district, Leadville, Colorado. (*After Emmons and Irving.*)

The most valuable ore consists of argentiferous galena and its secondary products, cerusite and cerargyrite. Lead is found also as anglesite and pyromorphite and occasionally as oxide. Silver occurs commonly as chloriodide and is very rare in the native state. The gangue minerals include quartz, chert, barite, siderite, and clay, the clay being commonly charged with iron and manganese oxides or with sulphates.

Alteration products of mixed pyrite and galena ore include limonite, jarosite, anglesite, and pyromorphite. Manganiferous siderite on oxidation yields manganese oxides.

Gold occurs in small flakes. Other minerals are zinc blende, calamine, arsenic and antimony (probably as sulphides), wulfenite, copper carbonate and silicate, and bismuth sulphide. Nodules of galena surrounded by lead carbonates are locally numerous in the oxidized zone.

In depth the ores consist of pyrite, sphalerite, and galena, with some chalcopyrite and other minerals.

In certain veins of sulphide ores below the porphyry contacts, some small masses of sphaleritic manganiferous ores are very rich in gold.[1] Silver is found as chloride and in general diminishes in quantity with increasing depth. The upper contact bodies as a whole were richest in silver; the "second contact" bodies were slightly lower in tenor; and at lower horizons the ore is of low grade.

Recently large bodies of iron-stained smithsonite and of monheimite have been found in the oxidized zones below lead-carbonate ores (see page 477).

Aspen, Colo.—The Aspen district, Colorado,[2] which lies southwest of Leadville, is an area of granite overlain by Paleozoic limestones, sandstones, and shales, which are intruded by dikes and sills of diorite porphyry and quartz porphyry. Structurally the district is a fault mosaic of folded beds, and the principal ore deposits have been formed by the replacement of limestone in and along fault fissures. The primary ore deposition was effected by ascending magmatic waters and took place in a relatively brief period, but according to Spurr[3] it had three successive stages, producing (1) barite veins, (2) silver sulphides, sulphantimonites, and sulpharsenites, (3) galena and zinc blende—each stage being preceded by slight fracturing of the rocks. The maximum deposition was below shale beds.

Near the surface the ores occur as oxides, sulphates, and carbonates, mixed with sulphides. With increase in distance from the surface the oxides, sulphates, and carbonates give place to pure sulphides. Argentiferous galena and blende are abundant in the deeper ore; other sulphides are of less common occurrence. Pyrite, chalcopyrite, and locally bornite also are found. Tetrahedrite and tennantite are common and contain a large proportion of silver. The gangue is quartz and barite.

In the Mollie Gibson and Smuggler mines there is much polybasite, which generally occurs in flesh-colored barite, the color

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[1] Butler, G. M.: Some Recent Developments at Leadville. *Econ. Geol.*, vol. 7, p. 318, 1912.

[2] Spurr, J. E.: Geology of the Aspen Mining District, Colorado. U. S. Geol. Survey *Mon.* 31, 1898.

[3] Spurr, J. E.: Ore Deposition at Aspen, Colorado. *Econ. Geol.*, vol. 45, p. 303, 1909.

being due to a small amount of iron oxide. Along watercourses the polybasite is reduced to native silver, so that the ore consists of pink and gray barite bound together by irregular wires and masses of silver.

San Juan Region, Colorado.—The San Juan region,[1] in southwestern Colorado, embraces a lofty plateau from which rise rugged mountains. The central group is termed the San Juan Mountains, and on its border are the Rico, La Plata, Engineer, Needle, and other mountains and mountain groups. The rocks in this region range in age from pre-Cambrian to Recent, and all the great subdivisions are represented. The dominant structural feature is a great dome, on the margin of which are smaller domes and laccoliths. Mesozoic and older rocks were folded and eroded, and on their steeply tilted edges the Telluride conglomerate, probably of early Tertiary age, was deposited. Above this conglomerate lie thousands of feet of volcanic tuffs, rhyolite, and andesite flows. Extensive sills and laccoliths of diorite porphyry have been thrust between the beds. Intruding the sedimentary rocks and lavas and locally cutting across the laccolithic sheets are great bodies of diorite and monzonite, which occur principally as stocks. Volcanic rocks predominate especially in the central, more elevated part of the area. The volcanic activity, which probably began in early Tertiary time, appears to have continued through most of that period. At several places within the region are hot springs, which are regarded as features of a declining volcanic era.

After the latest volcanic rocks were erupted the region was complexly faulted. Some of the faults are mineralized, among them the Amethyst fault at Creede, which carries the most productive silver deposit in the San Juan region.

The ore deposits of the San Juan region are in the main veins and related deposits. The central part of the region is noted for strong, persistent veins with bold outcrops. Many of them may easily be followed on the surface for thousands of feet. Not all the deposits are simple veins. The pipe-like deposits on Red Mountain, between Silverton and Ouray, and the ribbons of ore replacing limestone at Rico and Ouray are noteworthy.

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[1] Cross, Whitman, and Howe, Ernest: U. S. Geol. Survey *Geol. Atlas*, Silverton folio (No. 120), 1905.

Cross, Whitman: U. S. Geol. Survey *Geol. Atlas*, Telluride folio (No. 57), 1899.

Nearly all the deposits exhibit features of veins formed at moderate depths. A few veins near Rico and Ouray and in the Telluride quadrangle contain specularite, magnetite, and other minerals normally found at great depths, and a few deposits appear to have been formed at shallow depths. At least two periods of vein formation are indicated. The principal metals produced are silver, gold, and lead, with some zinc and a little copper. The production of the region, including Creede, is estimated at about $200,000,000. The principal districts are described below.

Silverton.—The ore bodies at Silverton[1] include lodes, stocks, and subordinate replacement deposits. Of these the lodes are the most valuable. The system of fissuring is of the coördinated type. The veins have steep dips; some strike northeast and others northwest. Some of them occupy fault fissures. The gangue consists of quartz, calcite, dolomite, rhodochrosite, rhodonite, kaolin, and fluorite. The metallic minerals include pyrite, tetrahedrite, sphalerite, chalcopyrite, galena, polybasite, ruby silver, argentite, and in some deposits tellurides of gold and silver in small amounts. As the lodes cut all the volcanic rocks of the region, their formation is regarded as not earlier than late Tertiary.

The Camp Bird vein,[1] which is at present the most productive deposit, is in the northwest corner of the Silverton quadrangle, but, because of transportation facilities, is tributary to Ouray It is near the Telluride district and generically is to be grouped with the Telluride lodes.

The Yankee Girl and associated deposits of Red Mountain are pipe-like masses in volcanic rocks. The ores down to about 200 feet from the surface were mainly silver and lead, galena and pyrite being the principal minerals. The ore below this zone is composed mainly of stromeyerite, bornite, chalcocite, and some gray copper and barite, yielding about 30 per cent. of copper and little or no lead. In depths below 600 or 700 feet the rich ore changed to pyritic material, that was too low grade to work. The ores in the copper-bearing zone were exceptionally rich, carrying several thousand ounces of silver to the ton.

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[1] Ransome, F. L.: A Report on the Economic Geology of the Silverton Quadrangle, Colo. U. S. Geol. Survey *Bull.* 182, 1901.

Woods, T. H., and Doveton, G. D.: The Camp Bird Mine, Ouray, Colorado. Am. Inst. Min. Eng. *Trans.*, vol. 33, pp. 499–550, 1903.

South of Silverton, in the Needle Mountains quadrangle[1] is the Bear Creek district,[2] a small area with thin quartz veins containing tellurides and other minerals.

Telluride.—The Telluride quadrangle[3] adjoins the Silverton quadrangle on the west, and the principal deposits are in the northeast corner of the quadrangle. The district is one of the most steadily productive in the San Juan region, yielding annually about $3,000,000 in gold and silver. The ore is concentrated, and tailings are treated in cyanide plants. The district includes the Liberty Bell, Smuggler-Union, and Tomboy mines. The Camp Bird mine, in the Silverton quadrangle, is essentially in the same group. The deposits are strong veins in rhyolites, andesites, and volcanic tuffs. The principal veins trend northwest; a smaller number have an east or northeast strike. The deposits contain gold and silver, and some carry both metals. There is no evidence of more than one period of mineralization. The ore minerals include quartz, calcite, siderite, adularia, rhodochrosite, barite, and fluorite, with gold, pyrite, chalcopyrite, sphalerite, and galena.

Ouray.—At Ouray,[4] north of the Silverton quadrangle, the deposits include veins and replacement deposits in quartzite and limestone. In the American Nettie mine thin veins in flat-lying quartzite extend upward to beds of shale. In the quartzite they form pockets of rich gold ores that lie parallel to the beds. About 600 feet below the horizon of the American Nettie deposits, in limestone below shale, are bedding-plane

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[1] Cross, Whitman, Howe, Ernest, Irving, J. D., and Emmons, W. H.: U. S. Geol. Survey *Geol. Atlas*, Needle Mountains folio (No. 131), 1905.

[2] Emmons, W. H.: Ore Deposits of Bear Creek, near Silverton, Colo. U. S. Geol. Survey *Bull.* 285, pp. 25–27, 1906.

[3] Cross, Whitman, and Purington, C. W.: U. S. Geol. Survey *Geol. Atlas*, Telluride folio (No. 57), 1899.

Purington, C. W.: Preliminary Report on the Mineral Industries of the Telluride Quadrangle, Colorado. U. S. Geol. Survey *Eighteenth Ann. Rept.*, part 3, pp. 745–850, 1898.

Winslow, Arthur: The Liberty Bell Mine. Am. Inst. Min. Eng. *Trans.*, vol. 29, pp. 285–307, 1899.

Rickard, T. A.: Ore Deposits, A Discussion (reprinted from *Eng. and Min. Jour.*), p. 88, 1903.

[4] Cross, Whitman, Howe, Ernest, and Irving, J. D.: U. S. Geol. Survey *Geol. Atlas*, Ouray folio (No. 153), 1907.

Irving, J. D.: Ore Deposits of the Ouray Quadrangle. U. S. Geol. Survey *Bull.* 260, pp. 54–77, 1905.

deposits containing pyrite and magnetite with garnet and actinolite, carrying about $12 gold to the ton. The ore body, though small, is an interesting illustration of a deposit containing minerals characteristic of the deep zone developed at moderate depths below flat-lying shale under conditions that presumably did not favor free circulation to the surface.

Rico.—The rocks of Rico[1] include Paleozoic limestones, sandstones, and shales, which rest on pre-Cambrian schists and are cut by dikes and laccolithic sheets of monzonite porphyry. The ore deposits include veins and ribbon-like masses that make out in limestone from the veins where they cross the contact of the limestone with overlying shale. In the lower levels of the mines, some 200 feet below the "contact," the ore is mainly quartz, pyrite, and chalcopyrite. In raising on the veins rhodochrosite, galena, sphalerite, and tetrahedrite become prominent. Upward, toward the "contact," the proportion of metallic minerals steadily increases, and the ore becomes much richer in gold and silver. The ore minerals include argentite, polybasite, stephanite, pyrargyrite, proustite, and native silver.

La Plata Mountains.—South of Rico are the La Plata Mountains,[2] a laccolithic group composed of Jurassic and Triassic sandstones and shales, intruded by huge sheets and dikes of monzonite porphyry. Both igneous and sedimentary rocks are cut by many veins that carry tetrahedrite, tennantite, pyrite, galena, sphalerite, chalcopyrite, and locally gold and silver tellurides. In the Neglected mine[3] a little native mercury occurs in the altered ore.

Lake City.—The ore deposits of Lake City,[4] east of Ouray, are

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[1] Cross, Whitman, and Spencer, A. C.: Geology of the Rico Mountains, Colorado. U. S. Geol. Survey *Twenty-first Ann. Rept.*, part 2, pp. 7–165, 1900.

Ransome, F. L.: The Ore Deposits of the Rico Mountains, Colorado. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 2, pp. 229–398, 1901.

Rickard, T. A.: The Enterprise Mine, Rico, Colo. Am. Inst. Min. Eng. *Trans.*, vol. 26, pp. 906–980, 1896.

Farish, J. B.: The Ore Deposits of Newman Hill. Colo. Sci. Soc. *Proc.*, vol. 4, pp. 151–161, 1892.

[2] Cross, Whitman, Spencer, A. C., and Purington, C. W.: U. S. Geol. Survey *Geol. Atlas*, La Plata folio (No. 60), 1899.

[3] Emmons, W. H.: The Neglected Mine and Near-by Properties, Durango Quadrangle, Colorado. U. S. Geol. Survey *Bull.* 260, pp. 121–127, 1905.

[4] Irving, J. D., and Bancroft, Howland: Geology and Ore Deposits near Lake City, Colo. U. S. Geol. Survey *Bull.* 478, 1911.

in Tertiary flows and tuffs which consist of andesites, rhyolites, latites, and basalts. These are cut by intrusive rhyolite, quartz latite, and quartz monzonite porphyry. The deposits are narrow veins, and some fill conjugated fissures. Their vertical range, according to Irving and Bancroft, is over 5,000 feet, and in their lower levels the primary minerals are chiefly quartz, galena, zinc blende, and pyrite. The ores formed at shallower depths include also tetrahedrite, rhodochrosite, barite, and jasperoid. The mineralization was probably effected at moderate depths by solutions connected genetically with the quartz monzonite intrusion or with some closely related deeper rock.

Many of the lodes are greatly fractured. Erosion is rapid, and the oxidized zone is not deep, extending generally not more than 100 or 200 feet below the surface. This zone contains iron oxides and sulphates, copper carbonates, and considerable anglesite, with some native copper and silver. Minerals below the oxidized zone include pyrargyrite, galena, and chalcocite. Native gold is present in the upper part of the zone of sulphide enrichment.

Creede.—The Creede district[1] is in Mineral County, near the headwaters of the Rio Grande. Mining operations began in 1891, and for several years the district produced over $3,000,000 annually. Altogether it has produced about $42,000,000. In order of importance the metals are silver, lead, gold, and zinc. Most of the ore was smelted without previous concentration, low rates being charged on account of its highly siliceous character. In late years mechanical concentration has been practiced. The district lies within the great Tertiary volcanic area of the San Juan Mountains, and no rocks other than Tertiary flows and intrusives are exposed within a radius of several miles. Eleven formations are recognized, each of which has been made up of one or more flows of rhyolite, andesite, or basalt, or of tuffs. Lake beds consisting of water-laid fragments of rhyolite and extensive deposits of travertine are found south of Creede. The lavas are intruded by dikes of quartz porphyry, quartz monzonite porphyry, and basalt.

The lava flows are deformed by complicated block faulting, and some of the faults have throws of more than 1,400 feet.

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[1] Emmons, W. H. and Larsen, E. S.: A Preliminary Report on the Geology and Ore Deposits of Creede, Colo. U. S. Geol. Survey *Bull.* 530, pp. 42–65, 1913.

The deposits are veins, for the most part occupying normal fault fissures; some of them follow porphyry dikes.

The Amethyst lode, the most productive deposit, has been exploited for about 9,500 feet along the strike and to depths of 1,000 to 1,400 feet below the surface. It strikes about N. 22° W. and dips 50° to 65° SW. It occupies a fault fissure between the rhyolite formations. At several places along the strike the vein splits to inclose horses of the country rock, and a number of small veins make off, especially in the hanging wall of the main fissure.

The subordinate fissures are especially well developed in the Last Chance mine. On level 6 a zone 100 feet wide includes six nearly parallel fissures, each from 6 inches to 4 feet wide. All of them dip westward, but the foot wall has the lowest dip, and the fissures projected join it below. Above this level the ground between the six fissures was highly altered and mineralized, and the ore body for a width of 100 feet was stoped.

The minerals that constitute the unoxidized ore in the lower levels of the Amethyst vein include zinc blende, galena, pyrite, chalcopyrite, gold, barite, and amethystine and white quartz. In the country rock along the vein secondary quartz, chlorite, adularia, and some sericite occur. Thuringite, a chlorite rich in iron, appears in the filled portion of the vein, as well as in the country rock near it. This mineral, which is unusual in western silver deposits, is one of the most abundant gangue minerals of the Amethyst vein. Except near the vein hydrothermal metamorphism is not pronounced.

At the outcrop, in the oxidized zone, and in the zone of partly oxidized sulphides, numerous minerals have been formed as a result of the weathering of the sulphide ores. These include limonite, hematite, pyrolusite, kaolin, jarosite, cerusite, smithsonite, anglesite, pyromorphite, cerargyrite, native silver, malachite, and jasper. Barite is more abundant in the upper levels than in the lower.

The most valuable deposits were silver-lead ores that were found 200 to 700 feet below the surface. Here and there in and below this zone occurs rich gold ore, consisting of sulphide ore locally oxidized, cut by veinlets of manganous oxide, some of which carry a high content of gold. A considerable body of this ore yielded $20 a ton in gold, which indicates notable enrichment, as the average content of gold in the mine is about $2 a ton.

Park City, Utah.—Park City,[1] a heavy producer of silver and lead, is about 25 miles southeast of Great Salt Lake, Utah. The sedimentary rocks of the district are of Pennsylvanian, Permian (?), Triassic, Jurassic (?), and Eocene age and consist of quartzite, limestone, shale, and sandstone. The Eocene rocks grade upward into andesite tuff and are overlain by andesite. The sedimentary rocks show no discordance in bedding. They are intruded by dikes, sills, stocks, and laccolithic masses of quartz diorite and quartz diorite porphyry. The andesite carries fragments of porphyry and is therefore younger than the porphyry. Boutwell concludes, for these reasons, that the quartz diorite and quartz diorite porphyry are as late as Triassic and probably older than the Eocene rocks on which the andesite rests.

MINE PRODUCTION IN PARK CITY MINING REGION, UTAH[a]

Year	Gold	Silver (fine ounces)	Copper (pounds)	Lead (pounds)	Zinc (pounds)	Total value
1914......	$99,183	2,955,008	1,559,953	32,323,066	3,173,313	$3,363,216
1915......	86,980	3,754,598	2,287,172	49,350,377	7,771,350	5,673,936
1870–1915.	4,145,295	129,461,654	28,230,670	1,185,495,505	55,853,076	158,128,516

[a] HEIKES, V. C.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 414, 1916.

The intrusion of igneous rocks was attended by the development of zones of garnet in limestone around the igneous bodies, and in some of these zones there are chalcopyrite, sphalerite, and other ores. The principal ore bodies, however, are not garnetiferous. The dominating structural feature is a great anticline, broken by many faults.

The ore deposits (Fig. 189) are replacement veins in limestone, quartzite, and porphyry. Although the limestones are interstratified with extensive beds of shale, the shale is not mineralized. The lode deposits are extensive, strong, and valuable. They lie in a few continuous master zones rather than in many small fissures. Examples are the Ontario, Daly West, Silver King, and Kearns-Keith fissure zones.

The earliest deposits were formed as large tabular bodies parallel to the beds. Later the great crosscutting fissure zones were formed and metallized. Some of these cut across the earlier de-

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[1] BOUTWELL, J. M.: The Geology and Ore Deposits of the Park City District, Utah, with Contributions by L. H. Woolsey. U. S. Geol. Survey *Prof. Paper* 77, 1912.

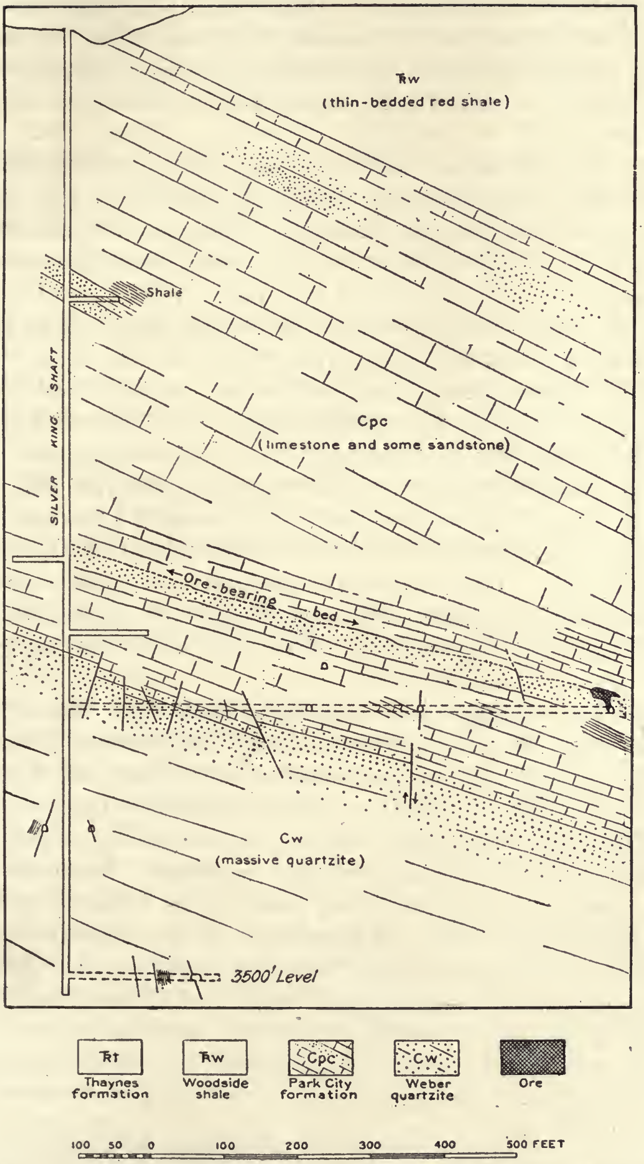

Fig. 189.—Geologic section through Silver King mine, Park City district, Utah. (*After Boutwell, U. S. Geol. Survey.*)

posits, and at many places ore shoots of contemporaneous age make out from them parallel to the beds. Thus there are bedding-plane deposits of two periods of metallization, but all the deposits are believed to be genetically related to intrusive rocks, for they are not found more than a few hundred feet from the intrusives.

The ore minerals are galena, pyrite, chalcopyrite, sphalerite, tetrahedrite, and the usual oxidation products. The gangue minerals are quartz, jasper, fluorite, calcite, and rhodochrosite. Barite is practically unknown in the deposits, the sulphates being represented only by alteration products. Where porphyry lies along the walls it is silicified and sericitized and contains pyrite. The bedded ores are generally richer than the lode ores.

Tintic, Utah.—The Tintic district,[1] in central Utah, yields complex smelting ores containing gold, silver, lead, and copper. Recently valuable zinc deposits have been developed. The total production from 1869–1915 is valued at $160,149,227. The area is occupied by a thick series of Paleozoic quartzite, slate, limestone, and sandstone, which are overlain by Tertiary rhyolite and andesite. These rocks are intruded by great masses of monzonite and by basalt dikes, and an andesite, equivalent to the monzonite, caps the rhyolite. The rocks are folded and extensively fractured and faulted.

After the folding of the Paleozoic sedimentary rocks erosion, which began with the Mesozoic uplift and continued into the Tertiary period, produced a surface with great relief. Upon this eroded surface volcanic material was poured out, the earlier rhyolitic lava filling deep canyons, on whose slopes talus was cemented by the rhyolite and later andesite. The more compact igneous and sedimentary rocks were fissured, and ores were deposited in them. Subsequently great masses of igneous rocks have been removed by erosion, with only slight changes in the topography of the limestone ridges, which had been buried by the lavas, thus exhuming the ancient topography.

The ore deposits are (1) large fractured zones in sedimentary rocks, chiefly in the limestone; (2) veins in igneous rocks; and

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[1] Tower, G. W., Jr., and Smith, G. O.: Geology and Mining Industry of the Tintic District, Utah. U. S. Geol. Survey *Nineteenth Ann. Rept.*, part 3, pp. 603–767, 1899.

Loughlin, G. F.: The Oxidized Zinc Ores of the Tintic District, Utah. *Econ. Geol.*, vol. 9, p. 1, 1914.

(3) contact-metamorphic deposits in sedimentary rocks near intrusive igneous rocks, mainly in limestone near monzonite.

The primary ore minerals include pyrite, galena, enargite, chalcopyrite, and tennantite. The gangue includes quartz, barite, carbonates, chalcedony, and gypsum. Oxidation products are limonite, hematite, anglesite, cerusite, cerargyrite, native sulphur, jarosite, copper carbonates, cuprite, native copper, and a large number of rare arsenic compounds that have resulted from the decomposition of enargite. Chalcocite and bornite become increasingly abundant in the lower parts of the oxidized zone.

Valuable oxidized zinc ores have recently been developed. Apparently they have been deposited by ground water that dissolved zinc from the sulphide bodies and migrated into the limestone wall rock. Zinc sulphate reacting on lime carbonate has precipitated smithsonite. In genesis these deposits are probably similar to the great zinc carbonate deposits recently developed at Leadville, Colo. (see page 476).

Lindgren[1] recognizes zones of deposition both horizontal and vertical.

1. In veins in monzonite quartz occurs in well-developed crystals with much pyrite and some galena, enargite, zinc blende, and chalcopyrite.

2. In the sedimentary rocks to a distance of 1 to 1⅓ miles north of the contact with the monzonite the gangue consists of fine-grained replacement quartz and much barite. The ores contain much enargite, with a little pyrite, tetrahedrite, and famatinite. There are a few shoots of lead ore, and the shoots of copper ore contain a little lead. The ores carry gold and about 20 ounces of silver to the ton.

3. Farther north in the same vein zones the deposits in the sedimentary rocks contain principally galena, with a little zinc blende and pyrite. The silver content is higher than in deposits farther south, the average of the ores being 30 or 40 ounces to the ton. There is practically no gold. The gangue consists of a fine-grained cherty material formed by the replacement of limestone and barite. This zone continues 1 to 1½ miles north of the end of the copper zone.

4. Farther north and east, beyond the lead-silver shoots, the

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[1] Lindgren, Waldemar: Processes of Mineralization and Enrichment in the Tintic Mining District. *Econ. Geol.*, vol. 10, pp. 225–240, 1915.

mineralization becomes more feeble. The gangue minerals consist of calcite, dolomite, and a little quartz; the ore minerals comprise galena and zinc blende, with a few ounces of silver to the ton.

Gold and copper thus occur on the whole near the monzonite; lead and silver mainly farther away. This arrangement, according to Lindgren, may correspond to deposition in successively cooler zones and a gradual spreading of the ore-forming solutions toward the north until they became so mingled with surface waters that ore deposition declined.

The variation in ore with difference in depth in individual mines is less marked, yet noteworthy. Ore shoots of gold, silver, and zinc have clearly been segregated by oxidation. The district is remarkable for an unusually low water level and great depth of oxidation. The water level in igneous rocks is 200 to 700 feet below the surface; in sedimentary rocks 1,650 to 2,400 feet below the surface. In the Gemini mine partly oxidized ores have been found 200 feet below the present water level. The ore as deep as level 21 of the Mammoth mine is oxidized and honeycombed like a gossan.

The oxysalts formed in lead and zinc mines consist of anglesite, cerusite, plumbojarosite, smithsonite, calamine, and hydrozincite; the copper mines yield many copper arsenates, malachite, and azurite, more rarely cuprite and native copper. Silver is present as argentite, cerargyrite, and native metal, and some rich oxidized ores show native gold. Covellite and chalcocite are found in the oxidizing copper ores, though nowhere in great masses.

PRODUCTION OF TINTIC DISTRICT UTAH[a]

Year	Gold (value)	Silver (fine ounces)	Copper (pounds)	Lead (pounds)	Zinc (spelter) (pounds)	Total value
1914......	$953,790	4,666,944	5,290,471	36,510,911	758,217	$5,700,837
1915......	916,755	4,370,984	5,357,932	32,657,018	3,845,058	6,082,169
1869-1915.	30,832,935	114,599,353	145,269,267	677,676,126	11,909,556	$160,149,227

[a] HEIKES, V. C.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 402, 1916.

Philipsburg, Mont.[1]—Philipsburg is in the western part of Montana, about 40 miles northwest of Butte. During the most

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[1] EMMONS, W. H., and CALKINS, F. C.: The Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78, 1913.

active period of mining on the Granite-Bimetallic lode (1881–1893) it was one of the most productive silver-bearing districts in the United States. In recent years its yield has been smaller. The Hope mine, one of the oldest in Montana, is also at Philipsburg. The Philipsburg quadrangle includes the Cable mine, at Cable and the Southern Cross, near by; also the Combination and Henderson mines, northwest of Philipsburg. The total production of the quadrangle is estimated at over $50,000,000, about four-fifths of which is in silver and all but a small amount of the remainder in gold.

The Philipsburg quadrangle is an area of sedimentary rocks ranging in age from pre-Cambrian to Pliocene, with intrusions of granodiorite and related rocks, probably belonging to the same period of intrusion as that of the Butte quartz monzonite and other batholiths in Montana.

The igneous masses, which intrude rocks as young as the Cretaceous, have caused pronounced contact metamorphism of the sedimentary beds, converting the calcareous members to garnet and tremolite zones and the argillaceous members to andalusite and scapolite rocks. Tourmaline is formed at considerable distances from the intrusives. Silica, iron, alkalies, fluorine, chlorine, and boron have been added to the sedimentary rocks surrounding the intrusive, probably by magmatic solutions.

No igneous intrusion or extensive deformation took place between Cambrian and late Cretaceous time, but the region was greatly deformed by folding and faulting in early Tertiary time, about contemporaneous with the period of igneous activity.

The ore bodies are contact-metamorphic deposits in sedimentary rocks, veins in various rocks, and bedding-plane deposits, including saddle deposits, in sedimentary rocks. All are in or near igneous bodies and probably were formed through the agency of magmatic waters. The deposits were probably formed in early Tertiary time at moderate depths—about 6,000 or 7,000 feet below the surface. Some of the veins carry pyrrhotite and specularite, and others tourmaline, indicating conditions approaching those of the deep-vein zone. The largest and most persistent veins, however, are free from these and other high-temperature minerals. They probably filled openings that connected freely with the surface at the time of deposition (see page 56).

In calcareous rocks the veins and bedding-plane deposits have formed largely by replacement of the walls. In shales and igneous rocks replacement has been less pronounced, but in igneous rocks there has been strong sericitization accompanied by the formation of carbonates and some sulphides.

The Granite-Bimetallic mine is working a strong vein in granodiorite, which carries chiefly silver but also considerable gold. It fills a wide fissure, which is joined by subordinate mineralized fractures. There is conclusive evidence of the enrichment of silver below the water level, and the rich silver ore contains also more gold than the low-grade silver ore in the bottom of the mine. The outcrop of this deposit carried some silver but very little gold, and after the discovery the location was allowed to lapse because of the small assay returns from the gossan. Richer ore with secondary cerargyrite, native silver, and ruby silver, in cracks across the older sulphides, appeared in considerable amounts 200 to 400 feet below the surface and extended to depths of 800 or 900 feet. The shoot of high-grade ore, which extended for about a mile along the strike of the deposit, followed, in a broad way, the present rugged surface (see Page 131). The gangue is rich in manganese. Zinc blende is abundant at several places in the primary ore below the richer sulphides. Some migration of gold has undoubtedly taken place. No associated placers have been formed.

The deposits of the Cable mine are included in a long, thin block of limestone, in contact on each side with quartz monzonite. Garnet and amphiboles occur in the limestone, but the ores are only locally associated with garnet. The principal minerals are calcite, quartz, pyrrhotite, pyrite, magnetite, and chalcopyrite, with chlorite, muscovite, and other silicates. The deposits were formed by replacement under contact-metamorphic conditions. Valuable placers were worked near the outcrop. Good ore was found at or very near the surface, and the tenor increased somewhat for a short distance below the surface. Some concentration has taken place by the removal of calcite and other valueless material more rapidly than gold, but there is no evidence of enrichment in gold below the water table.

At the Southern Cross mine[1] the deposits of oxidized gold ore fill a complex of fissures, of which some follow the calcareous beds and others cut across them.

The ore bodies of the Hope mine are extensive replacement de-

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[1] Billingsly, Paul: The Southern Cross Mine, Georgetown, Mont. Am. Inst. Min. Eng. *Trans.*, vol. 46, pp. 128–136, 1913.

posits in folded limestone, and most of them follow bedding planes. Some become wider at the crests of folds. A number of thin, nearly vertical veins cross the beds. Although the country rock is locally tremolitized, the ore bodies do not carry heavy silicate minerals. Extensive normal faulting followed the deposition of the ore bodies.

The Combination lode is an extensive bedding-plane deposit in tilted quartzite that dips about 15°. The great blanket-like deposit is broken into many blocks by normal faults (see Fig. 54, page 111). The ore is highly siliceous and carries silver and some copper. The grade decreases with increasing depth.

Comstock Lode, Nev.—The Comstock lode (Washoe district) is in Storey County, Nevada, about 20 miles southeast of Reno. At the end of 1912 it had produced about $380,000,000 in gold and silver, which is more than the production of any other precious-metal camp in the United States. About 60 per cent. of this sum is in silver and 40 per cent. in gold. Much of the ore was rich, over $30 a ton, but in recent years ore running below $14 a ton has been treated. In the early history of the district, when production was at its zenith—that is, in the seventies and eighties of the last century—the "Washoe" process (pan amalgamation) was extensively employed. In recent years the ore, as well as much of the old tailings, has been treated by cyanidation. Production has declined greatly, however, and is now less than $500,000 annually. The workings in depth are hot. Large volumes of hot sulphate water (170°F.) rise from the deepest workings and greatly hinder mining. At some places where the circulation is poor the men work 15-minute shifts in a blast of cold air and a spray of cold water. The Comstock lode has a certain distinction, also, as the place where Philip Deidesheimer invented "square-set" timbering, since then employed extensively elsewhere for supporting large chambers in heavy ground.

The lode[1] lies along a broad fault in late Tertiary rocks (Figs. 190 and 191). It strikes a few degrees east of north and dips

[1] King, Clarence: The Comstock Lode, in Hague, J. D., Mining Industry. U. S. Geol. Expl. Fortieth Par. *Rept.*, vol. 3, pp. 11–96, 1870.

Church, J. A.: "The Comstock Lode," New York, 1879.

Becker, G. F.: Geology of the Comstock Lode and the Washoe District. U. S. Geol. Survey *Mon.* 3, 1882.

Reid, J. A.: The Structure and Genesis of the Comstock Lode Cal. Univ., Dept. Geol. *Bull.*, vol. 4, pp. 177–199, 1905.

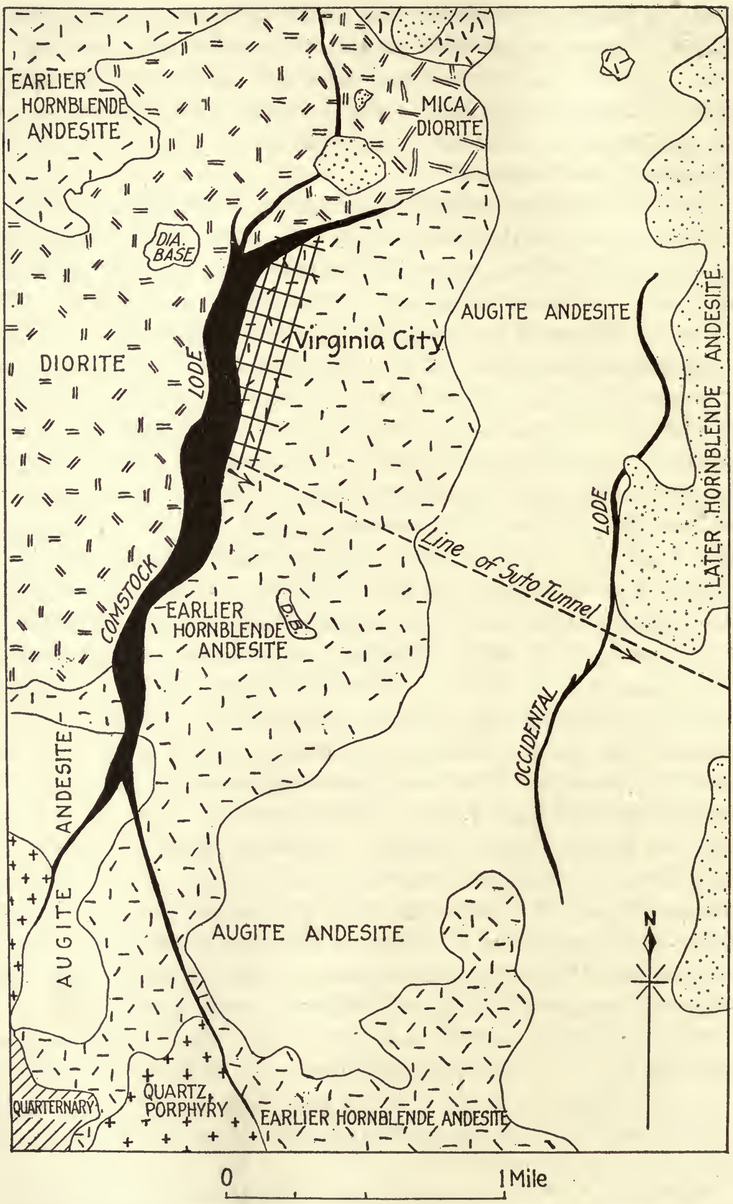

Fig. 190.—Geologic sketch map of Comstock lode and vicinity, Washoe district, Nevada. Black is quartz and vein matter. (*Based on map by Becker, U. S. Geol. Survey.*)

about 45° E. The foot wall is diorite, and the hanging wall is mainly diabase. This fault may be traced about 13,000 feet along the strike. The hanging wall was apparently shattered as it fell, and many nearly vertical fractures in it join the lode in depth. The structural relations (see p. 193) are somewhat similar to those of the Amethyst vein at Creede, Colo. and of the lodes at Tonopah, Nev.

The country rock is greatly altered by hydrothermal processes. Chlorite, sericite, and pyrite are developed and probably secondary orthoclase. Propylitization (page 249) is extensive. Along the fault is a body of quartz and vein matter several hundred feet wide. The ore shoots are found here and there in this quartzose material, and some of them make off in the hanging wall along secondary fractures. Much of the quartz is barren. The ore is composed of native gold, native silver, argentite, stephanite, and rich galena, with a little pyrargyrite, polybasite, horn silver, and sternbergite. Intimately associated with those minerals are iron and copper pyrites and zinc blende. The gangue is quartz with some calcite. Oxidation of the ore yields abundant manganese oxide, probably from the calcite.

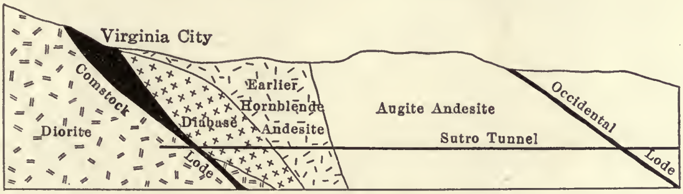

FIG. 191.—Section through Comstock lode, Nevada, on Sutro tunnel. Black is quartz and vein matter. (*After Becker, U. S. Geol. Survey.*)

After deposition much of the ore was fractured, and locally quartz by movement was reduced to powder. Since the period of crushing additional quartz and ore have been introduced into the fissure. In a few places, as in the 800-foot level of the Yellow Jacket mine, broken fragments of quartz, themselves containing ore, have been recemented by sheets of stephanite that have penetrated the cracks, and over the stephanite a secondary growth of quartz crystals has taken place.[1]

Placers of subordinate importance were worked in streams that head near the lode. These yielded electrum, a gold alloy rich in silver. It is said that the alloy near the lode carried only about

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[1] KING, CLARENCE: *Op. cit.*, p. 81.

25 per cent. of gold, but farther away it was richer. It was through the exploitation of these placers that the lode was discovered.

The Comstock lode was probably deposited by ascending hot waters at comparatively shallow depths. In many of its features it resembles deposits at Tonopah and Tuscarora, Nev., and at Pachuca and Esperanza, Mexico.

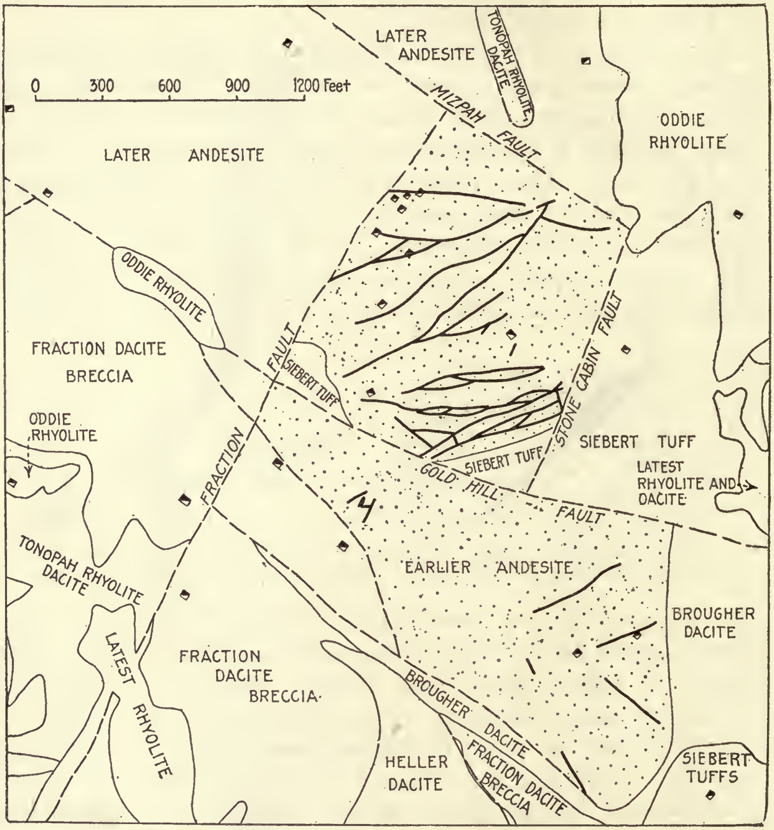

Fig. 192.—Geologic sketch map of part of Tonopah district, Nevada. (*After Spurr, U. S. Geol. Survey.*)

Tonopah, Nev.—Tonopah[1] is in the desert region of western

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[1] Spurr, J. E.: Geology of the Tonopah Mining District, Nevada. U. S. Geol. Survey *Prof. Paper* 42, 1905; Geology and Ore Deposition at Tonopah, Nev. *Econ. Geol.*, vol. 10, p. 713, 1915.

Burgess, J. A.: Geology of the Producing Part of the Tonopah District. *Econ. Geol.*, vol. 4, p. 681, 1909.

Nevada, about 160 miles southeast of Reno. All the rocks near Tonopah are of Tertiary age, probably Miocene and later, and all are eruptive except a series of water-laid tuffs which represent the accumulations, mainly of fine volcanic detritus, in a Tertiary lake (Figs. 192, 193).

Metal Production of Tonopah District, Nevada, 1914–1915[a]

Year	Producers	Ore (short tons)	Gold	Silver (fine ounces)	Copper (pounds)	Lead (pounds)	Total value
1914...........	23	531,278	$2,648,833	11,388,452	2,284	924	$8,946,987
1915...........	22	516,337	2,228,983	10,171,374	....	....	7,385,870
Total, 1904–1915	..	3,858,464	21,491,950	98,162,762	12,113	214,523	77,280,916

[a] Heikes, V. C.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 647, 1916.

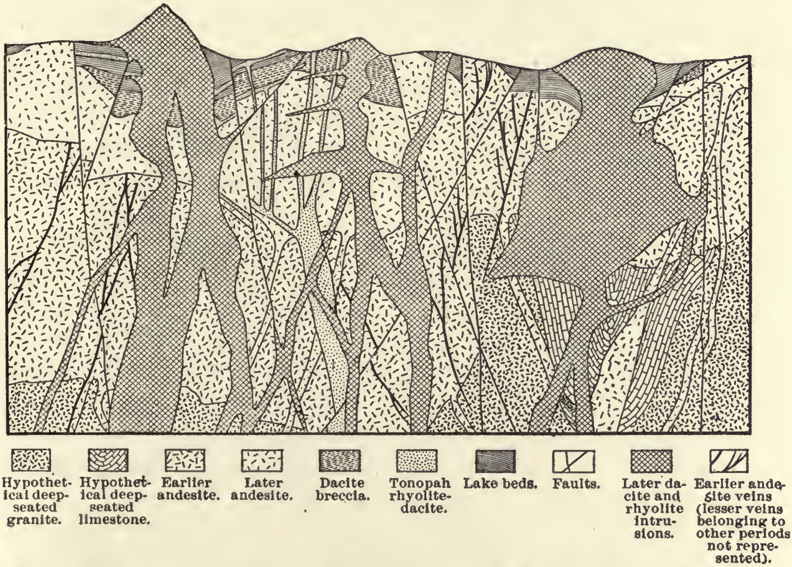

Fig. 193.—Ideal section to illustrate relations in the Tonopah district, Nevada. (*After Spurr, U. S. Geol. Survey.*)

The first eruption of the volcanic period was the Mizpah trachyte (formerly called the Earlier andesite). Later an andesite (somewhat more basic and formerly called the later andesite) was formed. Subsequently rhyolite and dacite were erupted and produced the volcanoes whose necks, left in relief by the erosion of the surrounding softer material, now form the hills around Tonopah.

The area occupied by the dacitic volcanic necks is coextensive with the region of observed complicated faulting. This faulting was probably initiated chiefly by the intrusion of the necks. After the intrusion and subsequent eruption there was a collapse, or sinking of various vents. The lava in sinking dragged down with it adjacent blocks of the intruded rock.

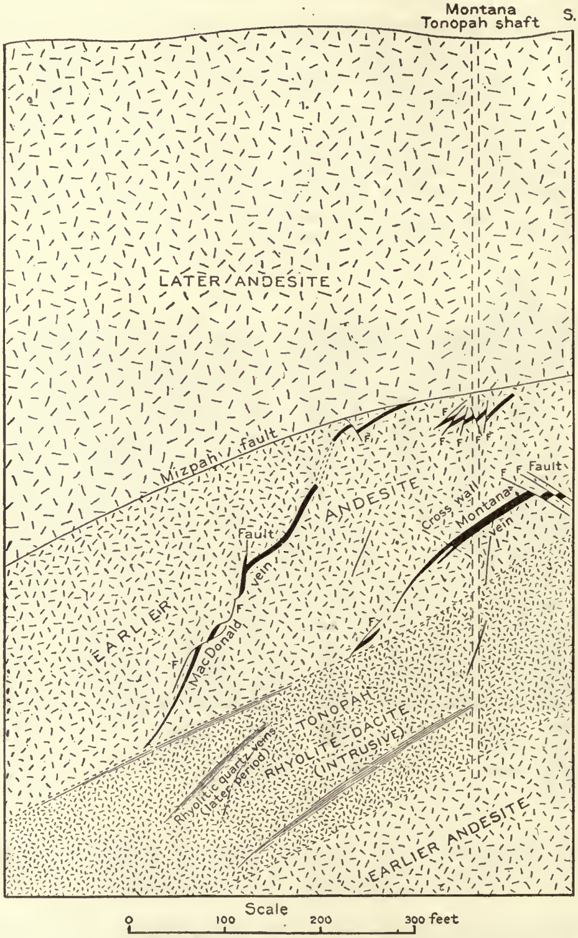

FIG. 194.—Cross-section of Montana Tonopah workings, Tonopah, Nevada. (*After Spurr, U. S. Geol. Survey.*)

The principal mineral veins, as shown by Spurr, occur in the Mizpah trachyte, and do not extend into the overlying rocks (Fig.

194). These veins have been formed, chiefly by replacement, along sheeted zones. Transverse fractures have determined the position of cross walls and ore shoots by limiting and concentrating the circulation. The mineralization was probably caused by hot ascending waters immediately after the earlier trachyte eruptions.

The zone of oxidation extends to greater depth in the more highly fractured places, and for this reason the brittle and more broken lodes are more deeply oxidized than the wall rock. The Mizpah vein is for the most part oxidized to a depth of 700 feet. The oxidized ore contains limonite and manganese dioxide, with horn silver and bromides and iodides of silver. The oxidized ore from the outcrop down is, according to Spurr, a mixture of original sulphides and selenides, together with secondary sulphides, chlorides, and oxides. At a depth of 500 feet in the Montana Tonopah mine good crystals of argentite, polybasite, and chalcopyrite have been formed freely in cracks and druses of the sulphide ore. These minerals are later than the massive ore. Pyrargyrite is formed in cracks in the oxidized ore, and some argentite fringes minute particles of horn silver as if secondary to it.

A series of veins, of little commercial importance, was formed after the eruption of the Tonopah rhyolite-dacite. These veins are characterized by irregularity and by lack of definition and persistence, though some are large. They may disappear by scattering and pass into a silicified wall rock. These veins are usually barren or contain only very small quantities of gold and silver. Barite, which is present in some of them, is not known in the veins in the earlier andesite.

CHAPTER XXVI

ZINC AND LEAD

ZINC

Mineral	Percentage of zinc	Composition
Goslarite	22.6	$ZnSO_4.7H_2O$.
Smithsonite	52.0	$ZnCO_3$.
Calamine	54.2	$Zn_2H_2SiO_5$ or $2ZnO.SiO_4.H_2O$.
Willemite	58.5	Zn_2SiO_4.
Hydrozincite	60.0	$ZnCO_3.2ZnO_2H_2$ or $3ZnO.CO_2.2H_2O$.
Zincite	80.3	ZnO.
Franklinite	16.0	$(FeZnMn)O.(Fe, Mn)_2O_3$.
Sphalerite (zinc blende)	67.0	ZnS.
Wurtzite	67.0	ZnS.

Zinc Minerals.—Sphalerite is by far the most abundant zinc mineral, although smithsonite and calamine are mined in considerable quantities in deposits that are altered near the surface. Nearly all zinc sulphide ores carry some lead; the western ores of zinc generally carry silver, and some of them carry both silver and gold. Pyrite, pyrrhotite, chalcopyrite, and galena are very commonly associated with sphalerite in sulphide deposits. The most common gangue minerals are quartz, calcite, and dolomite. Rhodochrosite and rhodonite are abundant in zinc ores at Butte, Mont. In some deposits the heavy silicates, such as garnet and actinolite, are intergrown with sulphides of zinc and lead.

Goslarite occurs on the walls of some mine workings as a white efflorescence. Owing to the high solubility of zinc sulphate in water, goslarite is comparatively rare in most districts.

Smithsonite is commonly found in the oxidized zones of zinc-bearing veins. It is most abundant in deposits in limestone. It has not been reported as a primary mineral in deposits formed by hot ascending waters. Where zinc sulphate waters attack limestone, smithsonite is deposited, calcium sulphate going into solution. The reaction is stated as follows:

$$ZnSO_4 + CaCO_3 + 2H_2O = CaSO_4.2H_2O + ZnCO_3.$$

The calcium sulphate precipitated as gypsum may remain with smithsonite or may be carried away in solution, as it is fairly soluble in cold water.

Calamine is commonly associated with smithsonite in the oxidized zones of zinciferous ores. It is not known as a primary mineral of ore veins deposited from hot solutions.

Willemite, the anhydrous silicate, is much less common than calamine. It is abundant in the primary ores of Franklin Furnace, N. J., but is not reported as occurring in the secondary ores at many zinc deposits.

Hydrozincite, the basic carbonate, occurs commonly in altered ores.

Aurichalcite, a basic carbonate of zinc and copper, is deposited by cold solutions, generally as drusy incrustations.

Sphalerite is the most abundant primary ore of zinc. At some places it has been shown to be secondary also. Wurtzite, as shown by Butler, is secondary in the San Francisco district, Utah. It is probably secondary at Butte, Mont.

Genesis of Zinc Deposits.—Zinc is rare in deposits formed by magmatic segregation but occurs in deposits formed at considerable depths and in contact-metamorphic deposits. In some deposits of the last-named class sphalerite is abundant. The great deposits of zinc in North America, which are associated with igneous intrusives, were formed for the most part at moderate depths. Zinc offers some puzzling problems in its concentration by enrichment. It dissolves very readily in sulphuric acid, and as a rule outcrops of zinc-bearing ores are leached of zinc. In calcareous rocks the zinc which is leached out of sulphide ores is deposited as carbonate by replacement of the lime carbonate around the older deposit. Some zinc that is dissolved in sulphate solutions descends and is deposited as secondary sphalerite and wurtzite.

The principal primary zinc sulphide is the isometric sphalerite. Wurtzite, the hexagonal zinc sulphide, is comparatively rare. In some occurrences the primary zinc minerals are oxides, such as franklinite, zincite, and gahnite, but these are rare or absent in sulphide deposits.

As zinc sulphide is easily dissolved in sulphuric acid sphalerite would not form in a highly acid solution. If, through reactions with the wall rock, the solution should become feebly acid or neutral, then zinc sulphide could be precipitated. Allen and

Crenshaw[1] state that sphalerite is precipitated from acid as well as from alkaline solutions, but that wurtzite is precipitated only from acid solutions and is probably always secondary. As zinc sulphide is one of the most soluble of the common sulphides it could not replace sulphides of copper, silver, or lead. Possibly it could replace pyrite, marcasite, or pyrrhotite under certain conditions, but no examples of its pseudomorphs after these minerals are known.

There is every reason to suppose that the zinc sulphide in carbonate rocks in the zinc deposits of southwestern Wisconsin has been dissolved by ground waters and has been reprecipitated as sulphide in large amounts where the solutions were in contact with reducing agents.

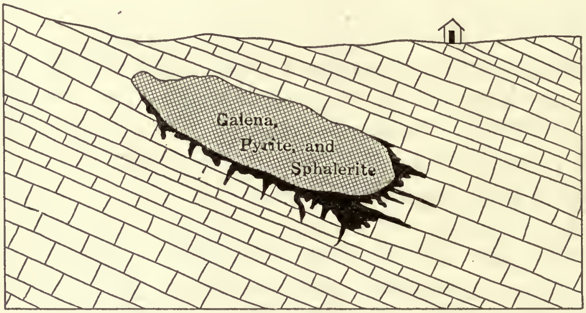

Fig. 195.—Ideal diagram showing a large mass of sulphide ore in limestone. The lead ore is partly oxidized but remains in place. By oxidation and leaching iron and zinc sulphates are formed and move downward. Zinc carbonate (black) is precipitated around the original ore body and in joints and bedding planes near it.

Secondary zinc blende has been found in western ore deposits in rocks other than limestone, but so far as the records show its occurrence in western deposits is rare. Large quantities of zinc are undoubtedly dissolved from the outcrops and oxidized zones of deposits in which it occurs as sulphide and are passed as sulphate downward, below the water level. Considerable amounts, however, may be carried in fissures and fractures that join the original deposit and be redeposited at some distance from the

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[1] Allen, E. T., and Crenshaw, J. L.: The Sulphides of Zinc, Cadmium, and Mercury; Their Crystalline Forms and Genetic Conditions. *Am. Jour. Sci.*, 4th ser., vol. 34, p. 359, 1912.

primary deposit.[1] On account of the greater solubility of their salts in an alkaline and reducing environment, zinc and iron migrate more extensively and farther from the original sources than gold and silver. At Tintic, Utah, valuable bodies of oxidized zinc ore[2] are found on the borders of older sulphide deposits. In this district and at Leadville Colo.,[3] and in the Cerro Gordo vein, California,[4] oxidized iron-stained zinc carbonate ores, unnoticed for many years, have lately become prominent sources of zinc (Fig. 195).

Joplin Region.—The Joplin region, which is mainly in southwestern Missouri, extends into neighboring portions of Kansas and Oklahoma. Although zinc and lead are found over an area of about 3,100 square miles, more than four-fifths of the output of the region comes from an area of 100 square miles centering about Joplin and Webb City, Mo. It is the most productive zinc-bearing region in the United States. The deposits have been known since 1850, and the mines have produced over 1,000,000 tons of lead concentrates and 5,000,000 tons of zinc concentrates. The ore in general is of low grade, and enormous tonnages are treated, especially of ore from the "sheet ground." Considering the nature of the deposits, the low cost of mining in this region is noteworthy.

LEAD AND ZINC PRODUCED IN MISSOURI IN 1915

District	Lead		Zinc	
	Quantity (short tons)	Value	Quantity (short tons)	Value
Southwestern Missouri...	26,534	$2,494,196	135,928	$33,710,144
Central and southeastern Missouri..............	183,906	17,287,164	372	92,256
State total, 1915.........	210,440	19,781,360	136,300	33,802,400

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[1] PENROSE, R. A. F., JR.: Certain Phases of Superficial Diffusion in Ore Deposits. *Econ. Geol.*, vol. 9, p. 20, 1914.

[2] LOUGHLIN, G. F.: The Oxidized Zinc Ores of Tintic, Utah. *Econ. Geol.*, vol. 9, p. 1, 1914.

[3] BUTLER, G. M.: Some Recent Developments at Leadville, The Oxidized Zinc Ore. *Econ. Geol.*, vol. 8, p. 1, 1913.

[4] KNOPF, ADOLPH: Mineral Resources of the Inyo and White Mountains, Cal. U. S. Geol. Survey *Bull.* 540, p. 97, 1914.

All the rocks[1] of the region are sedimentary. They dip southwestward at very low angles away from the Ozark uplift (Fig. 196). The surface is a rolling prairie. Carboniferous rocks only are exposed. These are for the most part Mississippian, but here and there small remnants of Pennsylvanian rocks are found. The following formations are represented:

Cherokee formation (Pennsylvanian): Shale, sandstone, and cool beds, top eroded; at some places it rests on Carterville, at others on Boone chert; at many places entire formation has been removed by erosion	0 to 150+
Unconformity.	
Carterville formation (Pennsylvanian): Shale and sandstone. Rests on eroded surface of Boone; not everywhere present	0 to 50
Unconformity, marked by an erosion surface of the Boone with valleys and ridges.	
Boone formation (Mississippian): A thick cherty limestone. It contains the Grande Falls chert member, from 15 to 120 feet thick. The top is an erosion surface subsequently covered by Pennsylvanian shale and sandstone. The Boone is the principal ore-bearing formation. The "sheet ground" is in the Grand Falls chert	145 to 485
Pre-Boone limestone, sandstone, and locally shale.	

During the two periods of erosion represented by the unconformities above and below the Carterville formation the Boone limestone was deeply trenched and a topography was developed characterized by underground drainage. Caves were formed, perhaps of the same order of magnitude as the Mammoth Cave of Kentucky, and limestone sinks were numerous. The country was near sea level,[2] and solution greatly exceeded

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[1] Bain, H. F.: Preliminary Report on the Lead and Zinc Deposits of the Ozark Region. U. S. Geol. Survey *Twenty-second Ann. Rept.*, part 2, pp. 23–228, 1901.

Smith, W. S. T., and Siebenthal, C. E.: U. S. Geol. Survey *Geol. Atlas*, Joplin District folio (No. 148), 1907.

Siebenthal, C. E.: Structural Features of the Joplin District. *Econ. Geol.*, vol. 1, pp. 119–128, 1906.

Buckley, E. R., and Buehler, H. A.: The Geology of the Granby Area. Mo. Bur. Geol. and Mines, vol. 4, 2d ser., 1909.

Haworth, Erasmus: Relation between the Ozark Uplift and Ore Deposits. Geol. Soc. America *Bull.*, vol. 11, pp. 231–240, 1900.

Siebenthal, C. E.: Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma. U. S. Geol. Survey *Bull.* 606, 1916.

[2] Buckley, E. R., Bain H. F. and others: "Types of Ore Deposits," p. 118, 1911.

stream erosion. On the surface there accumulated great bodies of residual chert, especially on hillsides and along cliffs bordering streams. This chert is typically shown in the Granby district, where it has been termed the "Granby" formation by Buckley and Buehler. The "Granby" and Boone were covered by the Carterville. Later the Carterville was eroded in places, and the Cherokee was deposited on the eroded surface of the Boone or, where it was present, on the Carterville. After the Boone had been buried below later beds it contained, at and near its top, water channels, such as solution cavities and buried talus of chert. In places the beds above solution cavities slumped down, producing solution faults.[1] The cavities and breccia were later cemented with ores.

The principal minerals are galena and sphalerite and their alteration products, smithsonite, calamine, etc. Some pyrite, marcasite, and chalcopyrite are also present, with their alteration products. The gangue consists of chert, calcite, aragonite, and quartz. Associated with the ore at many places is a hydrocarbon "tar," derived from organic matter originally in the sedimentary beds. Chert is abundant. The older residual chert is cemented by a later variety, presumably deposited from the ore-bearing solutions.

The deposits in the "sheet ground" are extensive and lie flat along certain horizons, mainly in the Grand Falls chert member. The ore zones are about 15 feet thick, and the ore has evidently been deposited around chert or in old solution cavities.

It is believed that ground waters dissolved the metals, that the solutions circulated in the breccia and ancient caves, and that the metals were deposited in them in part by reduction through the agency of organic material in the rocks. Buckley and Buehler held that the solutions moved downward from higher rocks, now generally eroded. Bain and Van Hise maintained that the solutions circulated down the southwest slope of the Ozark uplift and rose along faults in the Joplin region. Siebenthal found that some of the faults were formed by caving of beds above solution cavities, and as they did not extend below the cavities they could not offer deep channels. Siebenthal, however, attributes the metallization to ascending waters which circulated through cracks and joints. He reports many analyses of muds

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[1] SIEBENTHAL, C. E.: Structural Features of the Joplin District. *Econ. Geol.*, vol. 1, p. 119, 1906.

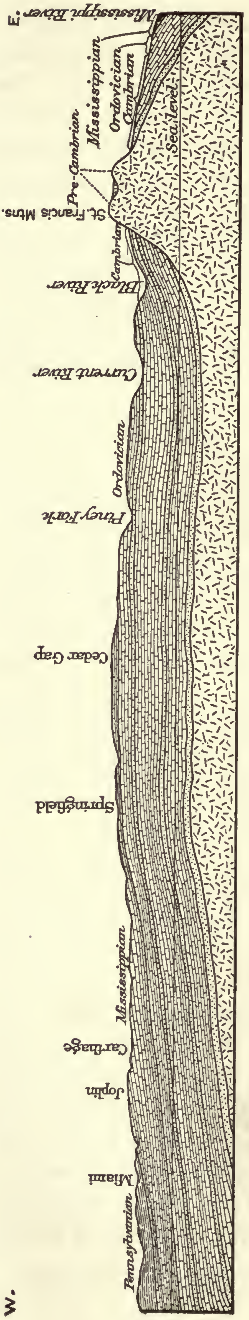

FIG. 196.—Geologic section of the Ozark uplift, Missouri. (*After Buckley.*)

that settled from artesian waters in this region and that were found to contain iron, zinc, and lead sulphides and a little copper.

The sedimentary rocks slope southwestward from the Ozark uplift. The waters following down the dip of the limestone beds dissolved the metals that were present in small amounts. West of Joplin the limestones are covered by impermeable shale, and this dammed back the waters, which rose through joints or other openings to the surface (see Fig. 196). In the limestone beds the waters, which carried carbonates, dissolved the metals and liberated hydrogen sulphide. As long as excess carbon dioxide was present the metals could remain in solution. Artesian waters, rising to-day from below the shale capping, contain lead, zinc, and hydrogen sulphide, and when these waters issue at the surface the carbon dioxide and hydrogen sulphide escape and sulphides are deposited. It is believed that the ores were deposited by the solutions rising to the surface through the limestone. Precipitation was accomplished by organic matter in the limestones and cherts and was facilitated by escape of gases to the surface. This hypothesis, as pointed out by Siebenthal, appears to be strongly supported by the position of the deposits with respect to structural features. They are grouped in the limestone near the edge of the Pennsylvanian shale, and in the region containing lenses of the Devonian shale they are practically absent except just under the edge of the shale, where there is a return flow of solutions.

Since deposition some of the ores have been oxidized, and some solution and reprecipitation have taken place. By removal of zinc and calcite galena has been concentrated near the surface; anglesite, smithsonite, and cerusite have been developed; and greenockite has been deposited on crystals of older sulphides.

Wisconsin Region.—In the upper Mississippi Valley, in southwestern Wisconsin, northwestern Illinois, and northeastern Iowa, are numerous deposits of zinc and lead.[1] The rocks of this area are limestone, sandstone, and shale. They dip very gently to

TENOR OF LEAD AND ZINC ORE AND CONCENTRATES PRODUCED IN WISCONSIN, 1914 AND 1915[a]

	1914	1915
Total crude ore, short tons	1,387,490	1,934,000
Total concentrates in crude ore:		
Lead, per cent	0.14	0.16
Zinc, per cent	8.02	7.32
Metal content in crude ore:		
Lead, per cent	0.11	0.12
Zinc, per cent	2.80	2.65
Average lead content of galena concentrates, per cent	73.70	73.50
Average zinc content of sphalerite concentrates, per cent	35.05	36.50
Average zinc content of zinc carbonate concentrates, per cent	27.50	24.90

[a] DUNLOP, J. P.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 126, 1916.

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[1] CHAMBERLIN, T. C.: The Ore Deposits of Southwestern Wisconsin. Wis. Geol. Survey, vol. 4, pp. 378–575, 1882.

VAN HISE, C. R.: Some Principles Controlling the Deposition of Ores. Am. Inst. Min. Eng. *Trans.*, vol. 30, pp. 102–108, 1900.

GRANT, U. S.: Lead and Zinc Deposits of Wisconsin. Wis. Geol. Survey *Bull.* 9, 1903.

BAIN, H. F.: Zinc and Lead Deposits of the Upper Mississippi Valley. U. S. Geol. Survey *Bull.* 294, 1906.

COX, G. H.: Lead and Zinc Deposits of Northwestern Illinois. Illinois Geol. Survey *Bull.* 4, 1910.

COX, G. H.: The Origin of Lead and Zinc Ores of the Upper Mississippi Valley District. *Econ. Geol.*, vol. 6, pp. 427–448, 582–603, 1911.

LEONARD, A. G.: Lead and Zinc Deposits of Iowa. Iowa Geol. Survey, vol. 6, pp. 9–66, 1897.

the southwest, and in places there are small shallow synclines. The rocks are fissured and heavily jointed. In some places, as in the Federal mine, faults with vertical displacements of over a foot occur, but there are no great faults in this region. Outcrops of igneous rocks likewise are lacking.

The rock section is shown below. The ores are principally in the Galena limestone, though some are in the Platteville limestone and some in the Maquoketa shale. Most of the workable deposits are near the base of the Galena, though some are in the upper part.

	Feet
Quaternary: Alluvium, terrace deposits, loess, residual clays	5 to 70
Silurian: Niagara dolomite	150
Ordovician:	
Maquoketa shale	160
Galena dolomite	240
Platteville limestone and dolomite	55
St. Peter sandstone	80
Shakopee dolomite	50
New Richmond sandstone	10 to 40
Oneota dolomite	200
Cambrian: Pottsdam sandstone with minor shale and dolomite	800
Pre-Cambrian: Quartzite with various igneous rocks.	

The generalized section at the main ore horizon is as follows:

	Feet
Dolomitic limestone (Galena), free from chert	50
Oil rock (Galena)	½ to 6
Shale or blue clay, called the "clay seam" (Platteville)	½ to 4
Brittle limestone, "glass rock" (Platteville).	
Magnesian limestone (Platteville).	

The shale or clay seam is at the top of the Platteville. The oil rock is an impure shaly limestone rich in organic matter, which according to David White,[1] is chiefly microscopic algæ. The oil rock, according to Rollin Chamberlin, is very porous and light, having a specific gravity of 1.98 and yielding gas bubbles when placed in water. One volume of the rock gave 57.46 volumes of gas when heated in a vacuum for two hours. Analysis of this material gave the following results:

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[1] Bain, H. F.: *Op. cit.*, p. 26.

ANALYSIS OF GAS FROM OIL ROCK OF DUGDALE PROSPECT, WISCONSIN[a]

Hydrocarbon vapors	11.11
Heavy hydrocarbons	4.00
CH_4	35.98
H_2S	6.79
CO_2	18.12
CO	8.40
O	0.26
H_2	13.18
N_2	2.21
	100.05

[a] BAIN, H. F.: *Op. cit.*, p. 26.

The ore deposits are in "crevices," in "runs," disseminated in beds, and in "flats and pitches." The crevices, termed by J. D. Whitney "gash veins," are fissures and joints enlarged somewhat by solution and cemented with ore. Certain beds appear to be especially favorable to concentration of the ore, and where these are cut by crevices, flat-lying irregular ribbons of ore are developed at and near the intersections. Such ore bodies are termed "runs."

The ore in the "flats" follows the flat beds, and the ore in the "pitches" follows crevices that pitch or dip away about 45° from either side of the vertical crevices. The pitches in a deposit join at the end, making in plan a long, slender ellipse where they intersect the oil rock. The form of the whole body has been compared by Chamberlin to the domestic flatiron (see page 81). As shown by Grant, this is a very common structural type, and frequently the interior of the ellipse is filled with low-grade disseminated ore, so that long, relatively narrow masses are worked. Deposits that are largely workable are commonly as much as 1,000 feet long, 75 feet wide, and 40 or 50 feet high.

The genesis of these deposits, as stated by Chamberlin, Grant, and Bain, is essentially as follows: The lead, zinc, and iron were originally deposited on the sea bottom at the time the Galena dolomite was laid down. The metals were probably in solution as sulphates and chlorides and were reduced by organic matter to sulphides at the time of their deposition. Later, when the beds, containing small amounts of metals, were elevated and the Maquoketa shale[1] was removed, a more active circulation was

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[1] According to Cox, the Maquoketa shale also carried original sulphides and was an important source of ore.

initiated. The waters were oxidizing, and the metals were then dissolved, probably as sulphates or as carbonates. The crevices, or enlarged joints, and the flats and pitches, opened by stresses and by settling of the limestone above the shrinking oil rock, were filled with ore, and the rock near by was replaced by the ore-depositing solutions. Locally the oil rock was replaced also. There was some brecciation of the ore itself as a result of further settling, and the fragments of ore were cemented by calcite and other minerals.

It is noteworthy that the clay seam at the top of the Platteville seals off an artesian circulation in sandstone beds below the Platteville.[1] The ores, which are mainly above the clay seam, must have been deposited by superficial waters. The gentle synclines which many of the deposits occupy are believed to be the original troughs of the sea bottom subsequently accentuated by moderate compressive stresses. In such troughs the oil rock is thickest and ground waters converge. The oil rock would shrink most where it was thickest, and fractures would be localized in thick parts of the oil rock, especially where thick parts were bounded by thin parts, thus permitting differences in amounts of settling.

The mineral composition of the ores is simple. They are made up of sphalerite, galena, marcasite, calcite, and rarely barite. Precious metals and cadmium are lacking. Quartz is practically absent. The wall rock is essentially unchanged near the ore deposits and shows no evidence of hydrothermal action. To a large extent the deposits fill fissures, though some replace the limestone wall rock. As a rule marcasite was formed first and was followed by sphalerite and that by galena. Near the surface sphalerite has been changed to smithsonite and calamine, and much zinc has been removed by solution, leaving a concentration of galena associated with limonite, anglesite, and cerusite. The lead sulphide persists at the very surface, and some deposits have been discovered by farmers when they plowed up galena in their fields.

Eastern Tennessee.—In eastern Tennessee zinc deposits are found at many widely separated places, but the principal deposits are between Knoxville and Morristown, in a belt about 40 miles long and a mile wide, and in Claiborne County about 35 miles

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[1] Bain, H. F.: "Types of Ore Deposits," p. 82, San Francisco, 1911.

north of Knoxville.[1] In southwestern Virginia[2] similar ores are found in similar rocks and possibly in an extension of the same belt. The zinc is of unusual purity, carrying little iron or lead, and commands a high premium in the market. Recently the American Zinc Co. has built three mills, two of which have a combined capacity of more than 2,500 tons daily. In 1915 Tennessee produced 32,912,902 pounds of zinc, valued at $7,318,405.

The rocks of this region are limestones, dolomites, and calcareous shales. They are closely folded and faulted. They strike northeast and dip from 10° to 45°. No igneous rocks are known in this vicinity. The deposits are in the Knox dolomite (Cambro-Ordovician); in Virginia this formation is called the Shenandoah limestone. Although they are not confined closely to any particular layer, in Tennessee the deposits are principally near the top and bottom of that formation. They are in the main bedding-plane deposits, but at some places the ores are developed along fault planes or brecciated zones, and locally their deposition appears to have been influenced by the folds in the limestone.

The ore minerals are sphalerite, galena, and pyrite. A little cadmium is present. The sphalerite is light-colored and nearly free from iron. The gangue is calcite and dolomite. In the Fall Branch group a hydrocarbon compound has been noted.[3] Oxidation has yielded the usual alteration products—smithsonite, calamine, anglesite, etc. There is not much pyrite in the ore, and in general oxidation has not extended to great depths.

Mineralogically these deposits resemble those of southwestern Missouri and southwestern Wisconsin. They are believed to have been formed by cold solutions.

Butte, Mont.—The Butte district is one of the largest producers of zinc in the United States—a distinction only recently achieved. In 1915 it produced 186,514,375 pounds of spelter. The geology of the district is discussed on page 357. It is an

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[1] Purdue, A. H.: The Zinc Deposits of Northeastern Tennessee. Tenn. Geol. Survey *Bull.* 14, 1912.

Keith, Arthur: Recent Zinc Mining in Eastern Tennessee. U. S. Geol. Survey *Bull.* 225, pp. 208–213, 1904.

Nason, F. L.: The Zinc Deposits of Eastern Tennessee. *Eng. and Min. Jour.*, vol. 99, p. 734, 1915.

[2] Watson, T. L.: Lead and Zinc Deposits of the Virginia-Tennessee Regions. Am. Inst. Min. Eng. *Trans.*, vol. 36, p. 681, 1905.

[3] Purdue, A. H.: *Op. cit.*, p. 60.

area of quartz monzonite crossed by several fracture systems, two of which are heavily mineralized. The oldest or easterly system of fractures includes the principal copper lodes, among them the Anaconda and Bell-Speculator vein systems. Of similar age and trend is the Rainbow lode, which lies only a few hundred feet north of the Bell-Speculator group. This lode, which received its name from its crescentic outline, is the largest and most productive silver lode of the district. It is made up of many closely spaced anastomosing veins of the replacement type. These crop out boldly and are heavily stained with iron and manganese. The upper portions have been worked successfully for silver. The most valuable silver deposits were found in the Alice mine, in which silver decreased with increasing depth and sphalerite appeared in great quantities around the 1,000-foot level. On the east end of the Rainbow lode, for about 2,000 feet along its strike, great zinc deposits have been developed in the Elm Orlu and Black Rock mines. In their upper levels both these mines were worked for silver. Zinc appeared in quantity at depths between 400 and 700 feet below the surface. Huge deposits are developed to the bottoms of these mines, which are opened to depths of about 1,700 to 1,900 feet below the surface.

The deposits are replacement veins and fractured zones, locally over 100 feet wide. The minerals include sphalerite, pyrite, galena, rhodochrosite, rhodonite, and quartz. Appreciable quantities of silver are present. Chalcopyrite, bornite, chalcocite, and other copper sulphides typical of the copper veins are found locally in the zinc deposits. Like the copper deposits of the Butte district, the zinc deposits appear to have been formed at moderate depths by deposition from ascending hot waters genetically related to igneous activities.

A noteworthy feature of these deposits is the absence of carbonates and silicate of zinc in the zone of oxidation. This is probably due to thorough leaching by sulphuric acid generated by the oxidation of abundant pyrite.

Coeur d'Alene District, Idaho.—The Coeur d'Alene region of Idaho has for many years produced considerable zinc as a by-product of the concentration of lead ore, and recently some of the mines have encountered in depth large bodies of zinc ore The Interstate-Callahan mine, one of the most productive zinc mines in the United States, yielded 45,226,949 pounds of spelter in 1915. It is about 7 miles northeast of Wallace. The rocks of the area are pre-Cambrian quartzite and slate cut by monzonite and related igneous intrusives.[1] The ore deposits are veins. The Interstate-Callahan mine is in the Prichard slate. The vein strikes about N. 58° W. and carries in places 14 feet of high-grade ore. The ore minerals are sphalerite, galena, pyrite, and quartz. Little or no siderite is present. Considerable silver is contained in the galena concentrate.

Franklin Furnace, N. J.—The Franklin Furnace district is in Sussex County, New Jersey, about 50 miles northwest of Jersey City. Although discovered as early as 1650, the deposits were not actively exploited until 1860. In 1915 the mines produced 272,084,000 pounds of zinc, figured as zinc oxide and spelter. This was recovered from 737,310 tons of ore. The larger part of the ore is concentrated, partly by magnetic processes, but a considerable amount is smelted directly. The residuum obtained from smelting some of the zinc ores carries 12 per cent. of manganese and 40 per cent. of iron. Much of this material is utilized for the manufacture of spiegeleisen, a product added to iron in making high-grade steel.

The rocks of the Franklin Furnace area[2] are pre-Cambrian gneiss and limestone and Cambrian limestone and quartzite. The ore deposits are in the southwest end of a band of limestone that extends northeastward 22 miles into Orange County, New York (Fig. 197). Both limestone and gneiss are bounded by later Cambrian limestone. The main deposits are at Mine Hill and at Sterling Hill, about 2 miles apart. Both are spoon-shaped, or synclinal, and pitch about 20° NE. The ore layer is from 1 to 100 feet thick, and the total length of the "keel" of the syncline at Mine Hill is 3,500 feet. The Sterling Hill deposit is a great mass of low-grade zinc-bearing material 250 feet wide.

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[1] Ransome, F. L., and Calkins, F. C.: The Geology and Ore Deposits of the Coeur d'Alene District, Idaho. U. S. Geol. Survey *Prof. Paper* 62, 1908.

[2] Spencer, A. C., Kummel, H. B., Wolff, J. E., and Palache, Charles: U. S. Geol. Survey *Geol. Atlas*, Franklin Furnace folio (No. 161), 1908.

Spencer, A. C.: The Mine Hill and Sterling Hill Zinc Deposits of Sussex County, New Jersey. N. J. State Geologist *Ann. Rept.* for 1908, pp. 23–52, 1909.

Nason, F. L.: The Franklinite Deposits of Mine Hill, Sussex County, New Jersey. Amer. Inst. Min. Eng. *Trans.*, vol. 24, pp. 121–130, 1895.

Kemp, J. F.: The Ore Deposits at Franklin Furnace and Ogdensburg, New Jersey. N. Y. Acad. Sci. *Trans.*, vol. 13, p. 76, 1894.

The ore minerals are unusual species: franklinite constitutes 50 per cent. of the ore, willemite 20 to 30 per cent., and zincite about 4 per cent. Other minerals are calcite, tephroite, zinc pyroxene, zinc spinel, zinc garnet, and axinite. Still other minerals, including sphalerite, have been deposited locally, especially near pegmatite veins that cross the ore bodies here and there.

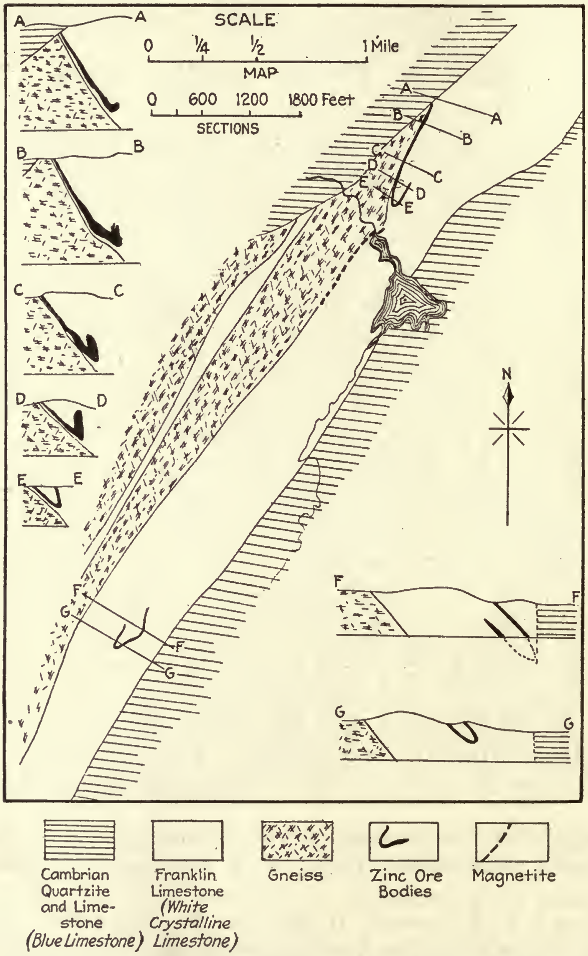

FIG. 197.—Geologic map and sections of Franklin Furnace region, New Jersey. (*Based on map by Spencer, U. S. Geol. Survey.*)

The zinc deposits grade into limestone and doubtless were formed by replacement of limestone. The origin of these deposits is a vexed problem, not yet solved. Nason suggests an origin connected genetically with the gneiss, which was formerly granite. Both Kemp and Spencer consider the probability of deposition by ascending magmatic waters. Such a deposit might be produced by close folding of an extensive bedding-plane deposit after oxidation. It is noteworthy that the granite now shows gneissic structure and has been metamorphosed by dynamic processes since it was formed. The ore minerals are somewhat metamorphosed but less extensively than the granite. The association of minerals formed ordinarily at high temperatures suggests processes of contact or dynamic-metamorphism.

LEAD

Mineral	Percentage of lead	Composition
Lead	100.0	Pb.
Minium	90.6	$2PbO.PbO_2$.
Massicot	92.8	PbO.
Plattnerite	86.6	PbO_2.
Pyromorphite	76.3	$3Pb_3P_2O_8.PbCl_2$.
Cotunnite	74.5	$PbCl_2$.
Anglesite	68.3	$PbSO_4$.
Cerusite	77.5	$PbCO_3$.
Galena	86.6	PbS.

Lead Minerals.—Of the lead minerals galena, cerusite, and anglesite are the most abundant. The gangue minerals quartz, chert, siderite, and calcite are their common associates. Most galena ores connected genetically with igneous rocks contain silver or gold or both. The silver in argentiferous galena is commonly supposed to be present as silver sulphide. Some zinc is generally found in lead deposits, and in many zinc ores lead is a valuable by-product.

In its primary deposits lead is restricted to fewer classes than copper. Economic concentrations in igneous rocks are unknown. Some lead is found in contact-metamorphic deposits and in veins formed at considerable depths, but in only a few of these is it abundant. It is characteristically developed at moderate depths and in deposits formed by cold solutions in calcareous rocks.

In North America deposits of lead associated with igneous rocks have been formed principally in late Cretaceous and early Tertiary time. These are characteristic of the "central belt" (page 404). Some lead is obtained, however, from deposits of Miocene age. Galena is present in a few deposits of the deep zone.

The percentage of lead in lead ores is variable. In the Coeur d'Alene region, Idaho, the ore averages about 7.8 per cent. In the disseminated deposits of southeastern Missouri the ore carries 3.6 per cent. In many regions either the lead is obtained as a by-product, or the ore carries besides lead, several other metals.

All natural salts of lead have low solubilities. The native metal and the oxides of lead (minium, plattnerite, and massicot) are of rare occurrence. Lead chloride is moderately soluble, so cotunnite does not accumulate in the oxidized zones of lead deposits. Lead chlorophosphate, pyromorphite, is much more common. Lead carbonate is very sparingly soluble, so cerusite is a comparatively stable mineral. Although the solubility of the sulphate anglesite is also low, it is nevertheless appreciable.

The transfer of lead as sulphate in small quantities was shown in experiments of Buehler and Gottschalk. As would be supposed from consideration of the relatively low solubility of its sulphate, lead is not extensively transferred in cold sulphuric acid waters. The salts that form under natural conditions coat the sulphides, retarding further action. Consequently lead sulphide dissolves slowly. It is dissolved in acid to only a slight extent and, like copper sulphide, would be deposited in an acid environment. Although several primary minerals contain lead, galena is the only one of these that is common. The chlorides, oxides, sulphates, and carbonates are probably formed as secondary minerals only. Lead, like gold, migrates very slowly in cold solutions.

Although native lead is found in a number of lead deposits, it is in very few so abundant as to become an important ore mineral. It is probably formed by reduction of oxygen salts of lead.

Pyromorphite is the principal metalliferous phosphate. It is an alteration product of lead ores that are exposed to waters carrying chlorine and phosphoric acid. In many deposits it is associated with limonite and commonly carries silver, possibly as finely divided cerargyrite.

Anglesite is known only as an alteration product, generally from galena. In many districts it is a valuable ore mineral in the oxidized zones of sulphide deposits.

Cerusite, unknown as a primary mineral, is common as an alteration product. It is an important ore mineral in many districts.

Galena is formed under many natural conditions. It is the principal primary ore of lead. The stability of galena in the oxidized zone has already been mentioned. Galena is commonly found in sluice boxes of placer mines and is plowed up in the fields of the southwestern Wisconsin zinc district. Even in districts where the climate is comparatively moist, galena is often found at the very outcrops of some ore veins.

Southeastern Missouri.—The disseminated lead deposits of southeastern Missouri[1] are about 50 miles south of St. Louis, in St. Francis and adjoining counties. These deposits produce about one-third of the lead of the United States.

TENOR OF CRUDE LEAD ORE AND CONCENTRATES IN SOUTHEASTERN MISSOURI DISSEMINATED LEAD ORE IN 1914 AND 1915[a]

	1914	1915
Total crude lead ore, short tons	4,718,300	5,067,800
Galena concentrates in crude ore, per cent	5.27	5.47
Lead content in crude ore, per cent	3.56	3.62
Average lead content of galena concentrates, per cent	67.60	66.50
Average value per ton of galena concentrates	$38.96	$45.89

[a] DUNLOP, J. P.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 85, 1916.

The geologic section, after Buckley, is stated below:

Cambrian:	Feet
Potosi dolomite	300+
Doe Run argillaceous dolomite	60 to 100
Derby dolomite	40
Davis formation; shale, limestone, and limestone conglomerate	170
Bonneterre magnesian limestone; sandy dolomite and shale (principal ore-bearing formation)	365±
La Motte sandstone	200

Unconformity.

Pre-Cambrian:

Granite and rhyolite with intruding diabase dikes.

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[1] BUCKLEY, E. R.: Geology of the Disseminated Lead Deposits. Mo. Bur. Geol. and Mines, vol. 9, parts 1 and 2, 1909; also in BAIN, H. F., and others: "Types of Ore Deposits," pp. 110–130, San Francisco, 1911.

WINSLOW, ARTHUR: Lead and Zinc Deposits. Mo. Geol. Survey, vols. 6 and 7, 1894.—The Disseminated Lead Ores of Southeastern Missouri. U. S. Geol. Survey *Bull.* 132, 1896.

The sedimentary beds, though generally flat, dip locally as much as 45°. They are cut by many faults that strike about northwest or northeast. Normal faults prevail, and single faults have vertical slips of less than 100 feet, but some fault zones have vertical shifts of as much as 700 feet. A little ore occurs in the Potosi dolomite, but most of it is in the Bonneterre limestone, especially near the base. Galena occurs also in the La Motte sandstone and in pre-Cambrian rocks but has not been mined successfully from the latter. The ore occurs as crystals and masses of galena disseminated in limestone or shale, as horizontal sheets along the bedding (Fig. 198), in small cavities or filling the small joints, and in shale and clay along faults. One ore body was 9,000 feet long, 5 to 100 feet thick, and 25 to 500 feet wide.

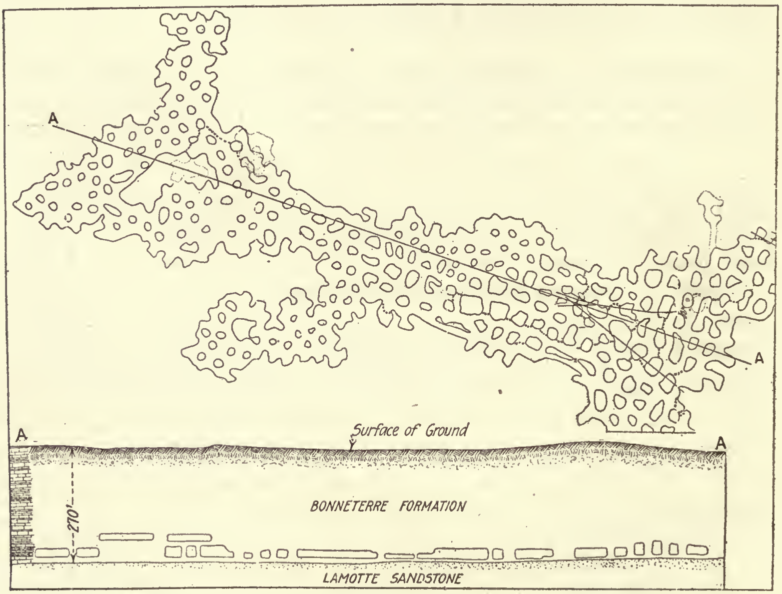

Fig. 198.—Mine map and cross-section of Desloge mine, St. Francis County, Missouri. (*After Buckley.*)

The limestone carries considerable organic material, and chlorite is extensively developed in it. The minerals of the deposits are galena with a little pyrite and at some places a little chalcopyrite or sphalerite. The gangue consists of calcite, chlorite, and a little quartz. The galena carries only about 2 ounces of silver to the ton of concentrates. At Mine LaMotte and Fredericktown cobalt and nickel sulphide are present, and formerly small amounts of these metals were recovered. Winslow names pyrrhotite as an associate of the ores, but Buckley does not mention it. Barite is associated with the ores in the Potosi formation.

Both Buckley and Winslow attribute the metallization to ground water. The lead was formerly widely dispersed in the Bonneterre and probably in other formations. It was dissolved and concentrated in fractures through which the solutions moved, being precipitated on contact with reducing agents in limestone or associated shale beds. Buckley considered the solutions to have been in part descending and in part ascending. Waters collected by him in mines contained alkalies and alkali earth carbonates, sulphates, and chlorides. Some carried as much as 15 parts per million of lead sulphate.

Although neither of these investigators has seemed to consider as probable any genetic connection with igneous rocks, Buckley[1] has noted the presence of basic igneous rocks in two places in St. Genevieve County, which joins the ore-bearing region on the east. These rocks appear to be intrusive in the Bonneterre formation and carry galena and sphalerite.

Coeur d'Alene District, Idaho.—The Coeur d'Alene district[2] of northern Idaho is in a mountainous country near the Montana

MINE PRODUCTION IN THE COEUR D'ALENE REGION, SHOSHONE COUNTY, IDAHO, 1884–1915[a]

Year	Gold	Silver (fine ounces)	Copper (pounds)	Lead (tons)	Zinc (spelter), (pounds)	Total value
1914	$64,157	12,178,194	4,242,662	169,849	41,523,383	$22,728,903
1915	46,433	11,158,955	1,941,296	164,199	69,685,003	30,119,424
1884–1915	5,476,257	142,222,795	62,806,908	2,283,256	170,688,937	315,456,316

[a] GERRY, C.N.: U.S. Geol. Survey *Mineral Resouces*, 1915, part 1, p. 551, 1916.

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[1] BUCKLEY, E. R., in BAIN, H. F., and others: "Types of Ore Deposits," p. 105, San Francisco, 1911.

[2] RANSOME, F. L., and CALKINS, F. C.: The Geology and Ore Deposits of the Coeur d'Alene District, Idaho. U. S. Geol. Survey *Prof. Paper* 62, 1908.

FINLAY, J. R.: The Mining Industry of the Coeur d'Alene District, Idaho. Am. Inst. Min. Eng. *Trans.*, vol. 33, pp. 233–271, 1903.

HERSHEY, O. H.: Genesis of the Lead-Silver Ores in the Wardner District, Idaho. *Min. and Sci. Press*, June 1, 8, 15, 1912.

border. It produces about one-third of the lead output of the United States and considerable silver, copper, gold, and zinc.

The lead-silver ores, which carry about 8 per cent. of lead and 6 ounces of silver to the ton, are concentrated in the district to a product containing about 50 per cent. of lead, and the concentrates are shipped to western smelters where high-grade lead ores are in demand for smelting siliceous ores of silver and gold.

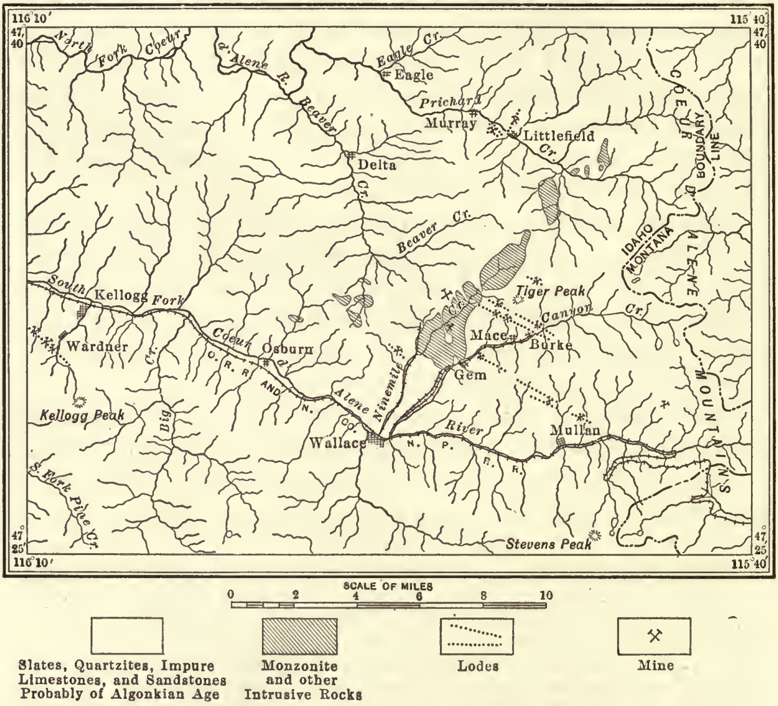

FIG. 199.—Sketch map showing position of lodes in Coeur d'Alene district, Idaho. (*After Ransome, U. S. Geol. Survey.*)

The copper ores, though of low grade, receive favorable rates from smelters that use them for lining converters.

The Coeur d'Alene district (Fig. 199) is an area of pre-Cambrian quartzites and siliceous slates that are intruded by large masses of monzonite and monzonite porphyry, with dikes of diabase and lamprophyre. The sedimentary section, as stated by Calkins, is given below.

	Feet
Striped Peak: Shales and sandstone, red and green	1,000
Wallace: Shales, more or less calcareous, interbedded with thin layers of siliceous and ferruginous limestones and calcareous sandstone	4,000
St. Regis: Shales and sandstones, purple and green	1,000
Revett: White quartzite, partly sericitic	1,200
Burke: Indurated siliceous shales with sandstones and quartzites, prevailingly gray-green	2,000
Prichard: Argillite, blue-gray to black, with distinct and regular banding, interbedded with a subordinate amount of gray sandstone. Uppermost part arenaceous and marked with shallow-water features. Base not exposed	8,000

The larger intrusive bodies are surrounded by aureoles of contact-metamorphosed sediments. The quartzites are altered to hornfels, and the uniform sandy layers and argillites to rocks composed of andalusite, garnet, sillimanite, mica, quartz, and feldspar. In the calcareous beds of the Wallace formation amphiboles and pyroxene are developed. Tourmaline and siderite are extensively deposited in quartzites at considerable distances from the intruding bodies.

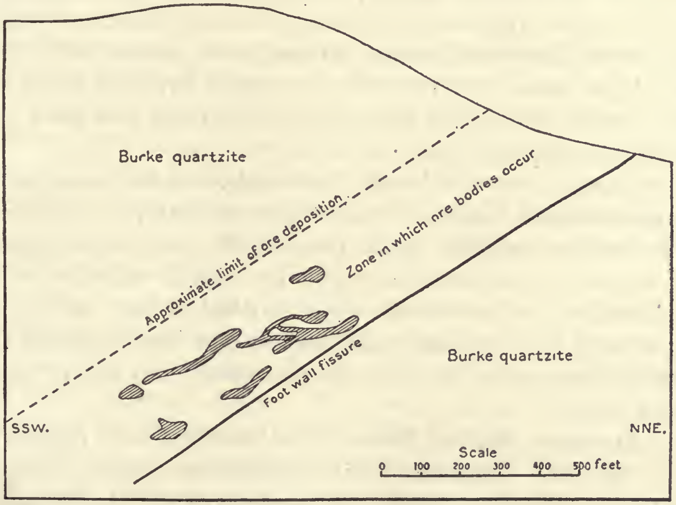

FIG. 200.—Section through Bunker Hill and Sullivan lode, Coeur d'Alene district, Idaho, showing relation of ore bodies to footwall fissure. (*After Ransome, U. S. Geol. Survey.*)

The rocks are extensively folded, and the folds are locally overturned. Slaty cleavage is developed in argillaceous members. The rocks are separated into many small blocks by normal and reverse faults many of which trend nearly northwest.

The most valuable deposits of the district are lead-silver lodes, most of which strike northwest, in the direction of the principal faults. These lodes, however, do not occupy the principal fault planes. Only one, the Bunker Hill and Sullivan lode, is formed along a fault of notable displacement, and this fault is one of less than 200 feet throw. The deposits of this lode, though along the fault, are principally in subordinate hanging-wall fractures (Fig. 200). The ores were formed partly by filling open spaces, but largely by replacement along zones of fissuring or shearing. The deposits, which have a vertical range of 4,000 feet, were probably formed under several thousand feet of rock, which has since been removed by erosion.

The ore minerals are galena, pyrite, chalcopyrite, and sphalerite, with some argentiferous tetrahedrite and stibnite. Siderite is the most abundant gangue mineral, but considerable quartz and a little barite are present. In depth pyrrhotite and magnetite appear, indicating conditions of the deep vein zone. Enrichment has probably been subordinate.

The deposits are cut by the lamprophyre dikes, showing that they were formed before the end of igneous activity. Moreover, the lead-silver deposits grade structurally and mineralogically into deposits of contact-metamorphic origin (Granite mine). These and other facts lead to the conclusion that the deposits were formed by ascending magmatic waters derived either from monzonite intrusions or from deeper-seated and nearly related igneous rocks.[1]

San Francisco Region, Utah.—The San Francisco region[2] embraces the San Francisco and neighboring ranges in Beaver County, southwestern Utah. On account of the Cactus mine it is known at present principally as a copper district, but its past product was mainly lead and silver.

The sedimentary series consists of Paleozoic limestone, shales, and quartzite. These beds were covered by lava flows, chiefly latites, probably of early and middle Tertiary age. Both the sedimentary rocks and the lava flows are intruded by large bodies of quartz monzonite and by aplite and basic dikes. Contact-

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[1] Butler, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah. U. S. Geol. Survey *Prof. Paper* 80, 1913.

[2] Ransome, F. L., and Calkins, F. C.: *Op. cit.*, pp. 134–140.

Mine Production in Beaver County, Utah, 1860–1915[a]

Year	Ore (short tons)	Gold	Silver (fine ounces)	Copper (pounds)	Lead (pounds)	Zinc (pounds)	Total value
1914	94,521	$20,717	288,821	1,511,888	9,337,928	7,143,746	$1,110,206
1915	53,814	13,028	279,694	428,916	8,589,416	2,989,811	1,004,333
Total, 1860–1915	......	680,593	20,481,211	42,732,610	400,134,334	25,404,650	45,188,345

[a] Heikes, V. C.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 398, 1916.

metamorphic deposits, with garnet, are developed near the quartz monzonite.

As stated by Butler, the ore deposits include (1) replacement deposits in fissures in the quartz monzonite; (2) replacement deposits in the limestone, including contact deposits and replacement deposits along fissures; and (3) replacement fissure deposits in the lavas.

Of the replacement deposits in fissures in the quartz monzonite the ore zone in the Cactus mine is the most valuable. This zone is brecciated quartz monzonite that has been altered and replaced by pyrite and chalcopyrite, with small amounts of tetrahedrite and galena and abundant specularite in a gangue of quartz, sericite, tourmaline, siderite, anhydrite, and some barite. Oxidation has not extended below 100 feet and for the most part is confined to a space within 50 feet of the surface.

The typical contact-metamorphic deposits are composed of pyrite, chalcopyrite, magnetite, and sphalerite in a gangue of garnet, tremolite, and other silicates. In general oxidation has not extended to great depth. The richer ores, however, have resulted from concentration in the oxidized zone.

The replacement deposits along fissures in the limestone are typically lead-silver ores containing minor amounts of copper and zinc. The ores are largely oxidized to the depth of present developments—500 to 600 feet. The metal-bearing minerals are principally carbonates with minor amounts of sulphates.

The Horn Silver mine is on the largest deposit in the volcanic rocks. This deposit occurs along a fault that has thrown the lavas down against the Paleozoic limestone. The lavas are shattered along this fault, especially in the vicinity of minor cross faults. The ore deposits have been formed largely by replacement of the brecciated lava. The primary ore consists of pyrite, galena, sphalerite, and minor amounts of other metallic minerals in a gangue of quartz, sericite, and partly altered lava. In the oxidized zone the ores are characteristically sulphates, anglesite being the principal mineral in much of the lead ore. Complex sulphates, such as beaverite, plumbojarosite, and jarosite, are rather abundant, and the oxidized copper ore carries much brochantite. Zinc is not abundant in the oxidized ores. In the secondary sulphide zone the copper ore consists of covellite and chalcocite, partly or wholly replacing sphalerite, wurtzite, pyrite, and, to a slight extent, galena. Rich copper ores were mined to a depth of about 750 feet, and enrichment along favorable channels has extended deeper. The rich zinc ores of this mine are composed of sphalerite and wurtzite, together with other sulphides. The wurtzite is secondary, forming around cores of sphalerite, and the richer ores have resulted from the addition of the zinc in the wurtzite. Normally the zinc enrichment extends to greater depth than the copper enrichment, and secondary zinc sulphide has been replaced by secondary copper sulphides.

CHAPTER XXVII

MISCELLANEOUS METALLIFEROUS DEPOSITS

MERCURY

Mineral	Percentage of mercury	Composition
Native mercury, quicksilver	100.0	Hg
Calomel	84.9	HgCl
Cinnabar	86.2	HgS

Mercury Minerals and Deposits.—Cinnabar is almost invariably primary; calomel and native mercury are generally confined to the superficial zones, where they are decomposition products. There are many other mercury minerals found almost exclusively in precious-metal deposits. Among them are coloradoite (HgTe) and schwatzite (mercury-bearing tetrahedrite). These minerals by weathering break down, yielding native mercury.

Calomel forms where chloride waters have access to quicksilver deposits that are undergoing oxidation. Its genesis is comparable to that of cerargyrite (AgCl), but as it is more soluble in water than silver chloride it is less stable. There is little evidence of extensive enrichment of quicksilver deposits. Decrease of tenor with increasing depth is probably a feature of the primary ore shoots. Some solution and redeposition are indicated, however, in a few deposits.

Cinnabar is the only important primary ore of quicksilver. It is almost invariably associated with calcite, chalcedony, and quartz. Barite, marcasite, and pyrite are commonly present, as are also realgar and stibnite. Chalcopyrite, galena, and precious metals are practically absent in some deposits. Bituminous matter is commonly associated with the deposits in the United States. Cinnabar is unknown in igneous rocks, in pegmatites, and in contact-metamorphic deposits. It is present in a few veins of the deep zone and in a larger number of veins formed at moderate depth, but practically all mercury deposits of economic value are veins or nearly related deposits formed in the shallow vein zone. Many of them fill openings, and some of them probably replace the country rock. The common association with igneous rocks and hot springs points to the agency of ascending hot waters. Many mercury deposits are of late Tertiary age.

The quicksilver deposits of California are in the Coast Range, extending northwest from a point near Santa Barbara about 400 miles to a point near Colusa. There are a few scattered deposits also in the north end of the State. This belt contains more than a score of districts that have yielded large amounts of quicksilver. The deposits are in rocks ranging in age from Mesozoic to Quaternary. Igneous rocks of Tertiary and Quaternary age are found at many places in this region: andesites, rhyolites, and basalts are present in many but not all districts. The deposits are veins, fractured zones, stockworks, or chambered breccia veins. They are found in metamorphic rocks, sandstones, tuffs, slates, serpentine, and gravel. In some deposits the ore impregnates and probably replaces sandstone.[1] In general the deposits decrease in size or give out in depth. In many of them operations ceased 300 or 400 feet below the surface. At the New Almaden mine, in Santa Clara County, however, the ore extended downward to the 1,600-foot level. The deposits were formed in late geologic time, near the surface at the time of deposition. Many of them are associated with hot springs. At the deposits of Sulphur Bank, Cal., and at Steamboat Springs, Nev., hot waters, depositing minerals, now issue (see page 263). These deposits were exploited until the heat became too great for the comfort of the miners.

The Terlingua district is in Brewster County, western Texas, near the Mexican border. Here Cretaceous limestone, shale, and marl are cut by Tertiary intrusives and in places are overlain by tuffs and flows. Rhyolites, basalts, and phonolite are present. The country is extensively faulted and shows a conjugate system of fractures. The ore is found in fractured zones and brecciated veins in limestone. A figure by Turner[2] shows two nearly vertical ore shoots in Lower Cretaceous limestone which appear to

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[1] Becker's argument opposes the view that wall rocks of these deposits have been replaced.

[2] Turner, H. W.: The Terlingua Quicksilver Deposits. *Econ. Geol.*, vol. 1, pp. 265–281, 1906.

terminate upward at or near shale. Calcite is the chief gangue mineral. Montroydite (HgO), terlinguaite (Hg_2ClO), and eglestonite (Hg_4Cl_2O), which have been identified only in this area, are probably decomposition products of cinnabar.

Deposits of cinnabar occur also in New Mexico, Nevada, Utah, and Oregon.

Recovery and Uses.—Mercury is recovered from its ores by distillation. The ore is charged in huge retorts or in shaft furnaces, where it is heated to a high temperature. The mercury vapors are condensed in brick chambers. Mercury is used for making explosives, alloys, drugs, paints, electric and other apparatus, for silvering mirrors, and for floating lights in lighthouses. Formerly large amounts of mercury were used in amalgamating silver ores by the Washoe and Reece River processes, but this use has now decreased nearly to the vanishing point, the practice being superseded by cyaniding, smelting, and other methods of beneficiation. Quicksilver is still used for amalgamation in many gold mills, and many cyaniding gold plants pass the pulp over amalgamation plates before it goes to cyanide tanks.

Production.—In 1875 the United States produced mercury valued at $4,228,538. The total production since mining began is valued at over $100,000,000. The production has declined in recent years, owing to the decreasing demand and lower prices, and also to the exhaustion of richer parts of the deposits. Stimulated by the demand from manufacturers of explosives, however, the output was greatly increased in 1915.

QUICKSILVER ORE TREATED IN THE UNITED STATES AND AVERAGE RECOVERIES, 1915[a]

State	Ore treated (short tons)	Metal recovered per ton (pounds)	Percentage of ore recovered as metal
Arizona Oregon Texas	7,321	45.3	2.27
California	129,521	8.3	0.41
Nevada	21,975	7.9	0.40
	158,817	9.9	0.497

[a] McCASKEY, H. D.: U. S. Geol. Survey *Mineral Resources*, 1915, part 1, p. 262, 1916.

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Summaries of the geology of the quicksilver deposits of the United States with bibliographies, are given in the following publications:

McCaskey, H. D.: U. S. Geol. Survey *Mineral Resources*, 1908, part 1, p. 683, 1909; also subsequent volumes.

Becker, G. F.: Geology of the Quicksilver Deposits of the Pacific Slope. U. S. Geol. Survey *Mon.* 13, 1888.

Turner, H. W.: The Terlingua Quicksilver Deposits. *Econ. Geol.*, vol. 1, pp. 265–281, 1906.

Phillips, W. B.: The Quicksilver Deposits of Brewster County, Texas. *Econ. Geol.*, vol. 1, pp. 155–162, 1906; Texas Univ. Geol. Survey *Bull.* 4, 1902.

ALUMINUM AND BAUXITE

Minerals	Percentage of aluminum	Composition
Diaspore	45.0	$Al_2O_3.H_2O$
Gibbsite	34.6	$Al_2O_3.3H_2O$
Bauxite	39.1	$Al_2O_3.2H_2O$
Alunite	19.6	$K_2O.3Al_2O_3.4SO_3.6H_2O$
Kaolin	20.9	$Al_2O_3.2SiO_2.2H_2O$
Sericite	20.4	$K_2O.3Al_2O_3.6SiO_2.2H_2O$
Corundum	52.9	Al_2O_3
Feldspars	.....	Variable
Nepheline	17.6	$NaAlSiO_4$
Cryolite	12.8	Na_3AlF_6

Aluminum Ores.—The principal ore of aluminum is bauxite. Diaspore and gibbsite are commonly present in bauxite ores. Alunite is utilized for the production of potash salts, and aluminum compounds are recovered as by-products. Patents have been issued for a process for the recovery of aluminum from kaolin, but the value of this process is problematical. Corundum is used as an abrasive. Kaolin, sericite, nepheline, and feldspars are protores of bauxite deposits. Aluminum is a constituent of many rock-making minerals. The metal constitutes 7.96 per cent. of the average of analyzed igneous rocks,[1] and it is present in considerable percentages in many sedimentary rocks, especially in shales and limestones. A list of all the minerals that contain aluminum is too long to be given here, but the more important ones are included in the above list.

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[1] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S .Geol. Survey *Bull.* 616, p. 27, 1916.

The superficial concentration of bauxite is closely analogous to that of iron oxide, and in some deposits both are found together. Both oxides also are commonly pisolitic in secondary deposits. As iron is concentrated from dunite, peridotite, or greenalite and sideritic rocks, so bauxite is concentrated from nepheline syenite, clayey limestone, and other rocks rich in aluminum, especially from those that supply abundant alkalies to solutions removing silica.

Uses and Production.—Aluminum is used in the manufacture of many articles where strength with lightness is required. Aluminum competes with copper as a conductor of electricity. It is used in the manufacture of alloys, chemicals, explosives, paints, etc.

Bauxite is used for the manufacture of aluminum and aluminum salts, including alundum, or fused alumina, which is used for an abrasive. Bauxite bricks are used for furnace linings.

The production of aluminum in the United States in 1915 was 99,806,000 pounds, valued at $17,985,500. The production of bauxite in the United States in 1915 was 297,041 long tons, valued at $1,514,834.

Arkansas.—The principal bauxite-producing areas in the United States are in Arkansas. The Bryant district is about 18 miles southwest of Little Rock; the Fourche Mountain district is immediately south of the city limits of Little Rock. These districts together produce about 80 per cent. of the bauxite of the United States. The earliest description of the region is that by Branner,[1] who discovered the deposits. The rocks of the region have been described by Williams[2] and the ore deposits by Hayes.[3] Recently detailed explorations have been made by Mead.[4] The region is one of folded Paleozoic sedimentary rocks intruded by large bodies of nepheline syenite. These rocks were eroded and locally were extensively weathered. Subsequently, probably in Tertiary time, they were covered with clays, sands, and gravels

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[1] Branner, J. C.: Bauxite in Arkansas. *Am. Geol.*, vol. 12, pp. 181–183, 1891.—The Bauxite Deposits of Arkansas. *Jour. Geol.*, vol. 5, pp. 263–289, 1897.

[2] Williams, J. F.: Igneous Rocks of Arkansas. Ark. Geol. Survey *Ann. Rept.* for 1891, vol. 2, 1891.

[3] Hayes, C. W.: The Bauxite Deposits of Arkansas. U. S. Geol. Survey *Twenty-first Ann. Rept.*, part 3, pp. 441–472, 1900.

[4] Mead, W. J.: Occurrence and Origin of the Bauxite Deposits of Arkansas. *Econ. Geol.*, vol. 10, pp. 28–54, 1915.

(see Fig. 201). The syenite, according to Mead, was more resistant to erosion than the surrounding softer rocks and stood above them in Tertiary time, and the bauxite deposits were eroded contemporaneously with the deposition of the lower Tertiary sediments, the result being that the bauxite was transported and interstratified with sands and gravels around the border of the syenite area and in depressions within it. Recent erosion has cut through the Tertiary sediments, exposing the underlying igneous rocks and the bauxite deposits.

The relations of the bauxite deposits to syenite and Tertiary rocks are shown by Fig. 201. Hayes, following Branner and Williams, considered the bauxite deposits to be the results of the

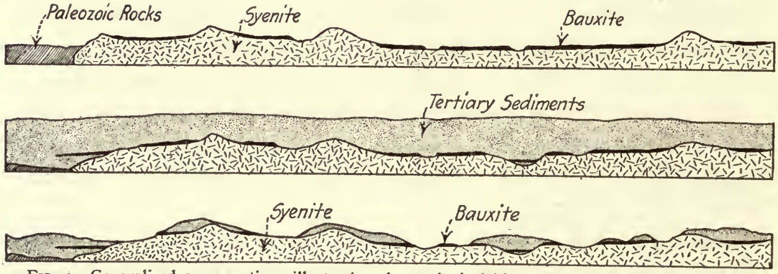

FIG. 4. Generalized cross-sections illustrating the geological history of the bauxite occurrences.

▨ Tertiary Sediments ■ Bauxite ▨ Syenite ▨ Paleozoic

FIG. 201.—Generalized cross-sections illustrating geologic history of Arkansas bauxite deposits. (*After Mead.*)

action of hot springs on the still heated syenite rocks or chemical sediments precipitated from solution in shallow salt water. Mead regards the deposits as products of normal rock weathering. He recognizes two classes of deposits: residual bauxite in place and transported detrital bauxite. The bauxite in place, which constitutes the most valuable deposits, grades downward into kaolin, which in turn grades into nepheline syenite. The bauxite deposits have very irregular outlines. The maximum known thickness of bauxite is 35 feet, but this is exceptional. The average thickness of merchantable ore is about 11½ feet. The surface exposed after the bauxite is removed is uneven and irregular. In places the underlying clay extends through the bauxite mantle to the surface, and throughout the bauxite beds there are horses and stringers of clay, so that about 40 per cent. of the material handled in mining is discarded.

The most common type of ore is a pisolitic or oolitic ore, made up of spherical grains of bauxite, some having concentric structure, in a bauxite matrix. These grains vary in size from microscopic bodies to those an inch or more in diameter. Here and there on an erosion surface of ore the pisolites are weathered out, yielding a gravel ore. Second in abundance is ore having the texture of the syenite, commonly called "sponge ore" or "granitic ore." This bauxite preserves in varying degrees the original granitic texture of the syenite and carries about 38.5 per cent. pore space. A third type of ore is amorphous and has the texture and appearance of clay. In much of the pisolitic ore the pisolites are scattered sparsely through an amorphous matrix, but some of the ore exhibits gibbsite bodies having the shapes of original feldspars.

According to Mead, syenite changes to bauxite by surface weathering. In the following table are analyses of samples from a cut near the Lantz mine. No. 1 is fresh syenite, No. 2 is partly kaolinized syenite, No. 3 is completely kaolinized syenite containing some bauxite, and No. 4 is bauxite.

Analyses of Samples Showing Gradation from Unaltered Syenite to Bauxite Ore

	1	2	3	4
SiO_2	58.00	52.64	39.80	10.64
Al_2O_3	27.10	29.56	37.74	57.48
Fe_2O_3	1.86	1.06	1.60	2.56
FeO	3.30	0.80	0.10	0.20
MgO	0.25	0.00	0.00	
CaO	1.62	0.00	0.00	
Na_2O	6.70	4.46		
K_2O	0.25	0.44		
TiO_2	0.40	1.20	3.30	1.20
H_2O	1.22	9.00	17.00	28.36

In Fig. 202 the volume compositions of the four samples are shown in terms of minerals and pore space.

The top of the bauxite deposits is higher in silica than the bauxite below. In many places it is necessary to remove the upper 18 to 24 inches of silicious material before mining.

This increase in silica toward the surface, according to Mead, may be due to downward concentration of alumina. Those portions of kaolin and halloysite which persist after the main portion of the kaolinized syenite has been altered to bauxite are the dense, impervious parts. Bauxite is soluble in surface solutions to a certain extent and on being dissolved and carried downward leaves the kaolin and hence the silica in relatively higher percentage at the surface. The alumina carried down is deposited below.

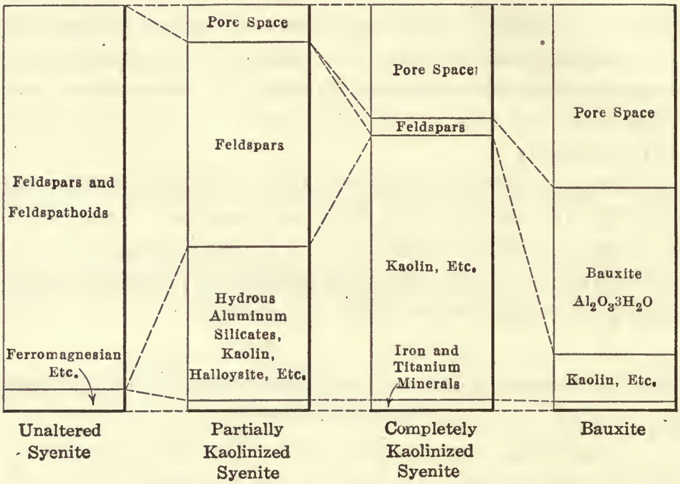

FIG. 202.—Diagram showing in terms of volume the mineral gradation from syenite to bauxite. Columns represent series of samples from a single locality near Lantz mine, Arkansas. (*After Mead.*)

Appalachian Districts.—In the southern Appalachian region, in a narrow belt[1] about 60 miles long, extending southwest from Adairsville, through Rome, Ga., and Rock River, Ala., bauxite deposits are found here and there in a residual mantle, 100 feet or more thick, that rests on sedimentary rocks, mainly on the Knox dolomite. Thrust faults are numerous; no igneous rocks are present. It is not certain that the alumina has been concentrated by simple processes of weathering from materials in the dolomite, or in sandy shale that was deposited above the dolomite. Below the dolomite is a heavy bed of aluminous (Cona-

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[1] HAYES, C. W.: The Geological Relations of the Southern Appalachian Bauxite Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 24, p. 243, 1894.—Geology of the Bauxite Region of Georgia and Alabama. U. S. Geol. Survey *Sixteenth Ann. Rept.*, part 3, p. 547, 1895.

sauga) shale, and Hayes suggested that waters ascending along faults have dissolved alumina from the shales and precipitated it near the surface. The origin of these deposits and their connection with faulting are, however, in doubt. Near Keenburg, Carter County, Tenn., bauxite is found as a large, irregular, deep pocket deposit in residual material resulting from the decomposition of the Knox dolomite.[1] Other deposits in Tennessee are probably residual also, and these appear to be closely similar to those in the Alabama and Georgia belt.

In Georgia, about 30 miles east of Macon, bauxite is mined[2] near the contact between the Tuscaloosa (Lower Cretaceous) and Claiborne (Tertiary) formations, which are made up chiefly of flat-lying unconsolidated clays and sands. The bauxite deposits rest directly on the Cretaceous clays or occur as nodules disseminated through them. Some beds are 10 feet thick.

CHROMIUM

The principal ore of chromium[3] is chromite, $FeCr_2O_4$ ($Cr_2O_3 =$ 68 per cent.). This mineral is a common constituent of basic igneous rocks, such as olivine gabbro, peridotite, and pyroxenite, in which it occurs as disseminated grains, as ill-defined streaks, and segregated in irregular masses. Peridotite and pyroxenite alter readily to serpentine, and much chromic iron ore is derived from serpentine. Chromite alters very slowly, and when serpentine bodies are weathered it may collect in gravel deposits or placers.

The principal use of chromite is in the manufacture of refrac-

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[1] Phalen, W. C.: Aluminum. U. S. Geol. Survey *Mineral Resources,* 1912, part 1, p. 951, 1913.

[2] Veatch, Otto: The Bauxite Deposits of Wilkinson County, Ga. Geol. Survey *Bull.* 18, p. 430, 1909.

[3] Diller, J. S.: Production of Chromic Iron Ore in 1913. U. S. Geol. Survey *Mineral Resources* 1914, part 1, pp. 1–13, 1915.

Vogt, J. H. L.: Beiträge zur genetischen Classification der durch magmatische Differentiationsprocesse und der durch Pneumatolyse entstandenen Erzvorkommen. *Zeitschr. prakt. Geologie,* 1894; Chromeisenerz, pp. 384–393.

Harder, E. C.: Some Chromite Deposits in Western and Central California. U. S. Geol. Survey *Bull.* 430, p. 180, 1910.

Glenn, W.: Chrome in the Southern Appalachian Region. Am. Inst. Min. Eng. *Trans.*, vol. 25, pp. 481–499, 1896.

Glasser, E.: Les richesses minérales de la Nouvelle Calédonie. *Annales des mines*, vol. 4, p. 299, 1903.

tory brick. Chromium is used for hardening steel and for the manufacture of chemicals and paints. Chromium salts are used in printing, dyeing, tanning leather, etc. The marketable ore generally carries 40 per cent. Cr_2O_3 or more. The production of chromic iron ore in the United States in 1915 was 3,281 long tons, valued at $36,744.

The largest deposits of chromic iron ore are in Rhodesia, Turkey, New Caledonia, and Greece. Chromite is widely distributed in areas of serpentine and other basic rocks in various parts of the United States. Such rocks are found at a few localities in the crystalline region east of the Appalachian Mountains and at many places in the Sierra Nevada and Coast Range in California. In the San Luis Obispo region, California, chromite ores are widely scattered in extensive serpentine areas. These deposits are said to have produced about 11,000 tons. Many of the deposits, according to Harder,[1] are in the serpentine near the contacts of older rocks into which the serpentine has been intruded. Such rocks may surround serpentine areas or may occur as masses within the serpentine. Hence deposits of chromite may extend around the borders of serpentine areas or may occur near included older rock masses within serpentine areas. Other deposits apparently have no such connection with older rocks. According to Pratt,[2] the chrome iron deposits of North Carolina have concentrated in the magmas through the action of gravity.

MANGANESE

Mineral	Percentage of manganese	Composition
Pyrolusite	60 to 63.0	MnO_2
Polianite	63.1	MnO_2
Psilomelane	45 to 60.0	$Mn_2O_3 \times H_2O$
Wad	....	Impure oxides
Manganite	62.4	$Mn_2O_3.H_2O$
Hausmanite	72.5	Mn_3O_4
Mallardite	19.9	$MnSO_4.7H_2O$
Alabandite	63.1	MnS
Rhodochrosite	47.6	$MnCO_3$
Rhodonite	41.9	$MnSiO_2$
Tephroite (manganese olivine)	54.3	$2MnO.SiO_2$
Spessartite (manganese garnet)	33.3	$3MnO.Al_2O_3.3SiO_2$

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[1] HARDER, E. C.: *Op. cit.*, p. 170.

[2] PRATT, J. H.: The Occurrence, Origin, and Chemical Composition of Chromite. Am. Inst. Min. Eng. *Trans.*, vol. 29, p. 17, 1899.

Origin of Deposits.—Manganese constitutes about 0.078 per cent. of the average igneous rocks.[1] In its chemical relations and in its geologic occurrence manganeses is closely related to iron. Its principal deposits are formed by concentration in superficial zones. Oxides and subordinately carbonates of manganese are deposited in bogs in much the same way as bog iron ores are formed. An example is afforded at Wicks, Mont., where manganese minerals have been dissolved in the weathering of granite and precipitated near the bottom of the gulch. Harder[2] states that the manganese was carried in solution at the surface and in underground waters that issue in springs near the bottom of the gulch. Parts of many sedimentary beds, as well as igneous rocks, are rich enough to yield manganiferous ores by superficial alteration and concentration. In general, contact-metamorphic deposits in the United States are comparatively free from manganese. The zinc deposits of Franklin Furnace, N. J., which have contact-metamorphic affiliations, are, however, highly manganiferous. Under conditions of weathering manganese oxides, like those of iron, tend to remain in the outcrop, and when other material is removed enrichment is accomplished. The gossans of some fissure veins have been worked for manganese. Some manganese is dissolved, however, and precipitated in depth forming deposits of secondary oxide. Manganese is dissolved and reprecipitated during weathering, somewhat more readily than iron.

Uses and Production.—The principal uses[3] of manganese in the United States are for making ferromanganese (Mn = 75 to 80 per cent.) and spiegeleisen (Mn = 12 to 20 per cent.). These compounds, with carbon, are added to molten iron to improve the quality of steel. Manganese is used also for making other alloys, for making dry batteries, disinfectants, glass, colored brick, paints, chemicals, etc. It is used for flux in melting silver and gold ores. Manganese ores carrying less than 40 per cent. of manganese normally do not command high prices.

Manganiferous zinc residuum is a furnace product consisting

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[1] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 27, 1916.

[2] Harder, E. C.: Manganese Deposits of the United States. U. S. Geol. Survey *Bull.* 427, pp. 135–137, 1910.

[3] Hewett, D. F.: U. S. Geol. Survey *Mineral Resources,* 1912, part 1, p. 215, 1913.

of manganese, iron oxides, and silicon, obtained from furnaces using New Jersey zinc ores. Small quantities of zinc residuum are used in the manufacture of spiegeleisen.

The marketed production of manganese ore in the United States in 1915 was 9,709 long tons, valued at $113,309. The imports of manganese ore for consumption were 313,985 long tons, valued at $2,633,286. The production of manganiferous ore (exclusive of those Lake Superior ores running so low in manganese as to be classed with iron ore) was 801,290 long tons. Large amounts of manganese ores are imported into the United States from Brazil, Russia, and India.[1]

Deposits.—Manganese deposits of the United States are found in rocks ranging in age from pre-Cambrian to Recent. In the eastern United States, on the Piedmont Plateau, the crystalline schists contain manganese, which, according to Harder,[2] is present as protoxide in amphiboles, pyroxenes, and other minerals and by weathering is concentrated to peroxide. With it are concentrated clay, iron oxide, and silica. The manganese is dissolved and reprecipitated by ground waters and is concentrated in nodules or cements, crevices and rock fragments.

In the Blue Ridge region, extending from Virginia to Georgia, the residual material from some of the sedimentary rocks contains concentrated deposits of manganese. These are superficial deposits and generally are mixed with clay and sand. As in the crystalline schists, the manganese in these deposits tends to segregate as nodules. It also fills cavities and seams and replaces sandstone. In west-central Arkansas Paleozoic rocks carry manganese. At Batesville[3] the manganese is found mainly in the Cason shale above the Polk Bayou limestone and below the Boone chert. Locally it is concentrated with clay by weathering, and on hillsides it has accumulated as eluvial deposits. Some deposits are 20 feet thick or more.

In the Cuyuna iron range, in Minnesota (page 311) irregular deposits of manganiferous iron ore are associated with the iron ore. The manganese content of the ore bodies varies greatly

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[1] Hewett, D. F.: U. S. Geol. Survey *Mineral Resources*, 1913, part 1, p. 62, 1914.

[2] Harder, E. C.: Manganese Deposits of the United States. U. S. Geol. Survey *Bull.* 427, pp. 46–47, 1910.

[3] Penrose, R. A. F., Jr.: Manganese, Its Uses and Deposits. Ark. Geol. Survey *Ann. Rept.* for 1890, vol. 1, pp. 145–147, 1891.

from place to place, small masses consisting of almost pure manganese oxide, and other portions containing only a few per cent. of manganese. However, deposits of considerable size average as high in manganese as 20 or 30 per cent.

In California beds and thin bodies of manganese ores are found in the Franciscan (Jurassic?) formation. These are generally only a few feet thick and are not extensive. At Golconda, Nev., a manganiferous bed lies between beds of calcareous tufa. The manganiferous oxidized ores of Leadville, Colo., and of Philipsburg and Butte, Mont., have been mined for manganese. The deposits of Franklin Furnace, N. J., which yield manganiferous zinc residuum, are mentioned on page 487.

NICKEL

Mineral	Percentage of nickel	Composition
Garnierite	....	$H_2(NiMg)SiO_2 + H_2O$
Annabergite	29.4	$Ni_3As_2O_8 + 8H_2O$
Millerite	64.7	NiS
Niccolite	43.9	$NiAs$
Chloanthite	28.1	$NiAs_2$
Gersdorffite	35.4	$NiAsS$
Pentlandite	22.0	$(FeNi)S$

Nickel Minerals and Ores.—Nickel is a common constituent of igneous rocks, in which it averages 0.02 per cent.[1] It is generally present in basic rocks, especially in those containing olivine. The principal nickel deposits have been formed by magmatic segregation or by superficial concentration from basic rocks. Nickel minerals occur also in vein deposits. Ferric salts attack nickel sulphide, and both the chloride and sulphate of nickel are soluble. From solutions the sulphide is precipitated by sulphides of iron. Nickel does not hydrolyze like iron to form the trivalent oxide; iron and nickel will separate by weathering, much of the iron remaining behind in the gossan, while the nickel is carried away in solution. The gossan of nickeliferous pyrrhotite deposits is essentially limonite. If arsenic is present nickel forms with it annabergite, or "nickel bloom," a moderately stable salt which is frequently found at the very surface and may indicate the presence of a nickeliferous deposit below. Hydrous

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[1] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 27, 1916.

nickel-magnesium silicates also are stable, and garnierite forms valuable deposits where nickeliferous basic rocks are weathering. It is a common alteration product of nickeliferous olivine (Fig. 203). The sulphate, morenosite, and the carbonate, zaratite, are soluble and do not accumulate except as incrustations of other minerals. Nickel sulphide is precipitated by hydrogen sulphide in neutral or alkaline but not in acid solutions. There is good evidence of the deposition of secondary nickel sulphides at least in small amounts. According to Kemp, secondary millerite was of economic value in the Lancaster Gap mine, Pennsylvania. Gersdorffite is secondary in some occurrences.

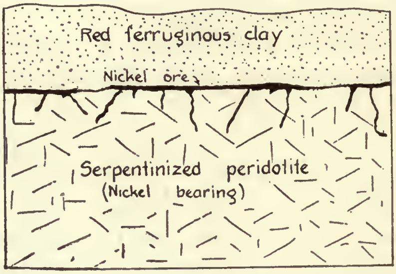

Fig. 203.—Ideal section of nickel-bearing serpentinized peridotite altering to red clay and garnierite. Nickel silicate ore accumulates below the clay and fills cracks extending into serpentine.

Pentlandite, which is probably primary in all occurrences, is the chief ore of nickel. It is found at Sudbury, Ontario, in deposits of sulphide ore formed by magmatic segregation, in which it is intergrown with pyrrhotite.[1] The crystals being invisible to the naked eye, this ore was long termed nickeliferous pyrrhotite. Nickeliferous pyrrhotite is found at Lancaster Gap, Pa.

Gersdorffite is present in the nickel deposits of Annaberg, Schneeberg, and other districts in the Erzgebirge, Saxony. It is probably the principal unoxidized constituent of the ore of the Nickel mine, Cottonwood Canyon, Nev.[2] At some places it is without doubt a secondary sulphide.

Uses and Production.—Nickel is used in the manufacture of many alloys—german silver, monel metal, etc. A small percent-

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[1] Campbell, William, and Knight, C. W.: Microscopic Examination of Nickeliferous Pyrrhotites. *Eng. and Min. Jour.*, vol. 82, p. 909, 1906.

[2] Ransome, F. L.: A Reconnaissance of Some Mining Districts in Humboldt County, Nevada. U. S. Geol. Survey *Bull.* 414, p. 67, 1911.

age greatly increases the strength and hardness of steel, and the larger part of the nickel recovered is used for making nickel steel and nickel-chromium steel. Nearly all the nickel used in the United States is obtained from the Sudbury district, Ontario. The ore of this district is smelted to nickel matte, which is shipped to refineries in the United States and Europe. The matte produced in Canada in 1913 was valued at $7,076,945.[1]

Nickel and nickel sulphate are saved from the electrolytes used in refining blister copper. Most blister copper carries a little nickel which goes into solution and accumulates in the electrolyte.

In 1915 in the United States 822 tons of nickel was recovered, valued at $538,222.

Sudbury, Ont.—The Sudbury nickel region, Ontario,[2] is in a hilly, glaciated country of moderate relief. The nickeliferous rocks are included in an elliptical area some 40 miles long and 20 miles wide, whose longer axis strikes north of east. The central portion of the ellipse, occupied by Upper Huronian or post-Huronian rocks, has been eroded to a peneplain, which is surrounded by a hilly belt of eruptive rock. The oldest series in the region consists of Huronian graywacke, slate, quartzite, and conglomerate, which are intruded by acidic and basic rocks. The Upper Huronian rocks (Animikie group) include conglomerate, tuffs, slates, and sandstones. Intruded between the Lower Huronian rocks or their igneous intrusives and the Upper Huronian sedimentary rocks is the great laccolithic mass, probably of Keeweenawan age, which contains the Sudbury nickel deposits. This great sheet dips toward its center, forming a canoe-shaped body which crops out in a rudely elliptical belt having a nearly plane surface. As a result of magmatic differentiation the lower portion of the laccolith is norite and the upper portion is micropegmatite, the two rocks grading into each other.

The ore deposits include (1) those formed by magmatic segregation, which occur between the norite and the underlying rocks, especially in depressions in the Huronian or in rocks intruded in

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[1] McLeish, John: Preliminary Report on the Mineral Production of Canada in 1913. Canada Dept. Mines, Mines Branch, 1914.

[2] Barlow, A. E.: Report on the Origin, Geological Relations, and Composition of the Nickel and Copper Deposits of the Sudbury Mining District, Ontario. Canada Geol. Survey *Ann. Rept.*, vol. 14, part H, 1904.

Coleman, A. P.: The Sudbury Nickel Field. Ontario Bur. Mines *Rept.*, vol. 14, part 3, p. 14, 1905.

the Huronian; (2) deposits of nearly related genesis in or near dikes of norite that extend outward from the lower contact of the main laccolithic body; and (3) deposits outside the laccolith, associated with norite intrusions, which possibly are connected with the principal body of the nickeliferous igneous rock beneath the surface. The ore consists chiefly of pyrrhotite, which contains small amounts of pentlandite and chalcopyrite. At many places it grades imperceptibly into pyrrhotitic norite. Fissures in the laccolithic rock are filled with quartz and sulphides, and along the contact with the older rocks sulphides have been deposited by contact-metamorphic processes. Pyrite is intimately associated with pyrrhotite. Other minerals are magnetite, niccolite, cassiterite, gersdorffite, polydymite, danite, galena, sperrylite, and gold. The gangue includes the rock-making minerals of norite, with some quartz, calcite, and other carbonates. Some of the deposits, as shown by Knight, exhibit evidence of the presence of aqueous solutions at the time of their deposition.

Alteration products include limonite, chalcocite, bornite, morenosite, annabergite, millerite, and probably several other species. Rounded hills of gossan, indicating the presence of sulphide ore beneath, extend almost unbroken for miles along the contact of norite with underlying rocks. The offsets and isolated masses of norite with which some of the ore bodies are associated are generally made brownish by the decomposition of disseminated sulphides. Locally the covering of gossan is as much as 6 feet deep, although its ordinary depth is 2 or 3 feet, and it merges into sulphide ore beneath. Chalcocite ores are not conspicuously developed. In the Vermilion mine, where the gossan is deepest, chalcocite and copper carbonate occur, and there is a concentration of platinum or sperrylite in the gossan.

Alexo, Ont.—The Alexo nickel deposit, in Dundonald Township, northern Ontario,[1] is nickeliferous pyrrhotite that occurs along a contact of serpentinized peridotite and rhyolite, the latter probably of Keewatin age. The solid pyrrhotite ore, about 5 feet thick, rests with sharp contact on the rhyolite. It passes gradually into ore mixed with serpentine. The ore minerals are pyrrhotite, pentlandite, magnetite, and chalcopy-

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[1] Uglow, W. L.: The Alexo Nickel Deposit, Ontario. Ontario Bur. Mines, *Twentieth Ann. Rept.*, part 2, p. 34, 1911.

Coleman, A. P.: The Alexo Nickel Deposit. *Econ. Geol.*, vol. 5, pp. 373–376, 1910.

rite. Well-formed crystals of olivine are surrounded by a matrix of pyrrhotite. Pyrrhotite veinlets cut the serpentine, and pentlandite occurs as stringers in pyrrhotite. Uglow believes that deposit was formed by replacement from aqueous solution, but Coleman considers it due to magmatic segregation.

Lancaster Gap, Pa.—At Lancaster Gap, Pa.,[1] pyrrhotite ores occur in amphibolite which is inclosed in mica schist. The deposits were worked for nickel before the Sudbury ores were developed. The amphibolite, which is probably an altered norite, carries pyrrhotite and chalcopyrite. Kemp considers these deposits as formed by magmatic segregation from norite.

New Caledonia.—New Caledonia[2] is the world's most productive nickel-bearing region except the Sudbury district. The deposits cap serpentine and peridotite and are covered by ferruginous clay. The ores are segregated in flat-lying deposits, veinlets, and stockworks. They have evidently been concentrated by weathering from nickeliferous serpentine and peridotite. The principal minerals are garnierite and other nickel silicates.

Riddle, Oreg.—At Riddle, Oreg.,[3] nickel silicate ores are formed from weathering peridotite.

COBALT

Mineral	Percentage of cobalt	Composition
Erythrite (cobalt bloom)	29.4	$Co_3As_2O_8.8H_2O$
Asbolite	32.0±	Oxides of cobalt and manganese
Jaspurite	64.7	CoS
Smaltite	28.2	$CoAs_2$
Cobaltite	35.5	CoAsS

Cobalt ores are found principally in veins and in deposits formed by magmatic segregation. Cobalt oxidizes readily under conditions of weathering. Cobaltite and smaltite are primary; asbolite and erythrite are secondary. Jaspurite is a rare sul-

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[1] Kemp, J. F.: The Lancaster Gap Nickel Mine. Am. Inst. Min. Eng. *Trans.*, vol. 24, p. 620, 1894.

[2] Glasser, E.: Rapport sur les richesses minerales de la Nouvelle Caledonie. *Annales des mines*, 10th ser., vol. 5, pp. 503–701, 1904.

[3] Kay, G. F.: Nickel Deposits of Nickel Mountain, Oregon. U. S. Geol. Survey *Bull.* 315, p. 120, 1907.

phide; of its genesis little is known. Asbolite is a hydrated oxide of uncertain composition in which are oxides of manganese and cobalt, the latter in some specimens amounting to 32 per cent. In deposits in New Caledonia it is a decomposition product of serpentinized peridotite.[1] It was common in the deposits of the Mine La Motte area, Missouri.[2]

Cobalt is obtained as a by-product from refining silver, copper, or nickel ores. The silver ores of Cobalt, Ontario,[3] are rich in cobalt, but comparatively little is recovered from them. Some cobalt is recovered from the Sudbury nickel ores. Nearly all the cobalt used in the United States is imported from Europe, where it is obtained principally from copper ores shipped from the Belgian Kongo,[4] some of which carry about 3.0 per cent. of cobalt. Formerly considerable asbolite was obtained from nickel mines in New Caledonia. Cobalt is used principally as a pigment. Refined cobalt sells at $1 to $2 a pound.

PLATINUM

The platinum of commerce generally contains small amounts of other metals of the platinum group—iridium, osmium, palladium, rhodium, and ruthenium. These metals are closely associated in nature, almost invariably as native alloys. Two other minerals of the platinum group are sperrylite ($PtAs_2$) and laurite (RuS_2). Platinum is found in basic igneous rocks, such as peridotites and dunites, and in serpentine derived by weathering of such rocks. By disintegration of these rocks and concentration in stream gravels, platinum accumulates in placers. Nearly all of the world's supply comes from the placers in the Ural Mountains.[5] The United States produced in 1915 about 8,665 ounces

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[1] Glasser, E.: Rapport sur les richesses minérales de la Nouvelle Calédonie. *Annales des mines*, 10th ser., vol. 5, pp. 503–701, 1904.

[2] Keyes, C. R.: A Report on the Mine La Motte Sheet. Mo. Geol. Survey *Rept.* 4, vol. 9, p. 82, 1895.

[3] Miller, W. G.: The Cobalt-Nickel Arsenides and Silver Deposits of Temiskaming. Ontario Bur. Mines *Rept.*, vol. 19, part 2, pp. 12, 17, 1913.

[4] Ball, S. H., and Shaler, M. K.: Mining in the Belgian Congo in 1913. *Min. and Sci. Press*, vol. 108, pp. 320–325, 1914.

[5] Purington, C. W.: The Platinum Deposits of the Jura River System, Ural Mountains, Russia. Am. Inst. Min. Eng. *Trans.*, vol. 29, pp. 3–16, 1899.

Lindgren, Waldemar: Platinum and Allied Metals. U. S. Geol. Survey *Mineral Resources*, 1911, part 1, p. 987, 1912.

of platinum and allied metals, valued at $478,688. Practically all the platinum produced in the United States is derived from black sand in California and Oregon and by refining the mud that forms in vats where blister copper is purified electrolytically. Some of the platinum reported as produced in the United States should be credited to Sudbury, Ontario, as copper and nickel mattes from that region are refined in the United States, and the muds are treated for recovery of platinum. Sperrylite is found in the superficial zone of some of the Sudbury mines,[1] also in the Rambler mine, Wyoming,[2] and near Moapa, in eastern Nevada.[3] It is not an important source of platinum. Platinum and palladium are found with gold in ores of the Boss mine, in the Yellow Pine district, Clark County, Nevada.[4] The ore minerals are associated with quartz that replaces dolomite along vertical fractures. Granite porphyry intrudes the dolomite, and no basic igneous rocks are known in this region. The ore is oxidized and contains a bismuth-bearing variety of plumbojarosite. The platinum appears to have been reconcentrated by surface agencies.

ANTIMONY

Mineral	Percentage of antimony	Composition
Native antimony	100.0	Sb
Cervantite	78.9	Sb_2O_4
Senarmontite	83.3	Sb_2O_3
Valentinite	83.3	Sb_2O_3
Bindheimite	.....	$Pb_3Sb_2O_8 + xH_2O$
Tetrahedrite	24.8	$4Cu_2S.Sb_2S_3$
Jamesonite	29.5	$Pb_2Sb_2S_5$
Bournonite	24.7	$PbCuSbS_3$
Stibnite	71.4	Sb_2S_3

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[1] Barlow, A. E.: Report on Origin, Geologic Relations, and Composition of the Nickel and Copper Deposits of the Sudbury Mining District, Ontario. Canada Geol. Survey *Ann. Rept.*, vol. 14, part 1, p. 97, 1904.

[2] Emmons, S. F.: Platinum in Copper Ores in Wyoming. U. S. Geol. Survey *Bull.* 213, pp. 94–97, 1903.

[3] Bancroft, Howland: Platinum in Southeastern Nevada. U. S. Geol. Survey *Bull.* 430, p. 192, 1910.

[4] Knopf, Adolph: A Gold-Platinum-Palladium Lode in Southern Nevada. U. S. Geol. Survey *Bull.* 620, pp. 1–18, 1915.

Stibnite, bournonite, and jamesonite are primary; the antimony oxides and native antimony are secondary. In weathering activities antimony minerals resemble those of lead; the metal tends to remain or accumulate in zones of oxidation. Stibnite is by far the most abundant ore of antimony. It occurs in quartz veins and related deposits formed chiefly at moderate and shallow depths. Many of them replace limestone.

Antimony is recovered from its ores by roasting or by smelting. In antimony-lead ores it is recovered as antimonial lead, which is used for making type metal. Antimony is also used for making "hard" lead, metal for bearings, and many other alloys, drugs, paints, mordants for dyeing, and fireworks, for vulcanizing rubber, and for many other purposes. Wet methods are utilized for making antimonial salts.

The production of antimony in the United States is small. Nearly all of the domestic supply comes from China, France, Algiers, Austria, and Mexico. A little is obtained from slimes as a by-product of refining copper and precious-metal ores. In 1915, stimulated by high prices resulting from the war, the domestic production reached 5,000 tons of ore containing 2,000 tons of antimony, worth about $325,000.

Deposits of antimony 40 miles southwest of Marysvale, in southern Utah,[1] have produced antimony valued at over $100,000. The ore consists of stibnite and its oxidation products, which occur in small flat-lying deposits, in the sandstone and conglomerate.

Near Gilham, Sevier County, Ark.,[2] deposits of antimony occur in Paleozoic sandstones and shales. These rocks are thrown into regular parallel folds, and in the country northeast of Gilham the Paleozoic beds and later rocks are cut by many small igneous intrusives. The ore deposits are thin tabular masses which generally follow the bedding planes; some are as much as 100 feet long, 40 feet wide, and 2 feet thick. The original minerals are quartz, stibnite, jamesonite, zinkenite, galena, sphalerite, pyrite, chalcopyrite, siderite, and calcite. Comb quartz is developed. Traces of gold and silver are present. Oxides and the sulphide of antimony or lead ores prevail for 40 to

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[1] Richardson, G. B.: Antimony in Southern Utah. U. S. Geol. Survey *Bull.* 340, pp. 253–256, 1908.

[2] Hess, F. L.: The Arkansas Antimony Deposits. U. S. Geol. Survey *Bull.* 340, pp. 241–252, 1908.

115 feet from the surface, below which sphalerite and other sulphides appear. According to Hess, the deposits have probably formed through the agency of hot waters.

In 1915 the largest production of antimony was obtained from deposits near Wild Rose Spring, in the Panamint Range, California. These deposits contain stibnite and antimony ocher. Deposits 30 miles northeast of Mojave and at many other points in Kern County, in the east end of San Benito County, and near Grass Valley, Calif., were also mined, and considerable quantities were produced at several places in Nevada. The Fairbanks district, Alaska, produced about 625 tons of stibnite ore carrying 58 per cent. of antimony.

ARSENIC

Mineral	Percentage of arsenic	Composition
Native arsenic	100.0	As
Realgar	70.1	AsS
Orpiment	61.0	As_2S_3
Tennantite	17.0	$4Cu_2S.As_2S_3$
Enargite	19.1	Cu_3AsS_4
Arsenopyrite	46.0	FeAsS

Enargite and arsenopyrite are the principal sources of arsenic. Both are primary. Realgar and orpiment are both primary and secondary; native arsenic is secondary. The commercially valuable deposits of arsenic are principally lodes formed at moderate depths. Arsenic minerals are common in many gold and copper ores, and arsenopyrite has been found at many places in the Appalachian region. At Brinton, Floyd County, Virginia, arsenopyrite deposits in mica schist are mined and the ore is calcined for white arsenic.[1] Near Carmel, N. Y., stringers of arsenopyrite occur in gneiss. Arsenopyrite is mined for arsenic at Monte Cristo, Wash.[2]

In the recovery of arsenic from its ores they are crushed and charged into earthenware retorts. The arsenic volatilizes on the

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[1] HESS, F. L.: The Arsenopyrite Deposits of Brinton, Va. U. S. Geol. Survey *Bull.* 470, p. 209, 1912.

WATSON, T. L.: "Mineral Resources of Virginia," p. 210, 1907.

[2] SPURR, J. E.: Geology and Ore Deposits of Monte Cristo, Wash. U. S. Geol. Survey *Twenty-Second Ann. Rept.*, part 2, p. 803, 1901.

application of heat and condenses in a vessel at the mouth of the retort. Redistillation in the presence of air will yield the oxide. Arsenic is produced also in the electric furnace. The greater part of the arsenic produced in the United States is a by-product from the gases of copper furnaces, particularly from plants smelting enargite ores of Butte, Mont., and Tintic, Utah. The fumes from the furnaces are conducted through a labyrinth of chambers, on the walls of which arsenic oxide is deposited. This is subsequently refined by roasting in cylindrical revolving furnaces, from which the fumes are again conducted through chambers. The United States produced 5,498 tons of arsenious oxide in 1915, valued at $302,116. Arsenic and its compounds are used for making Paris green, drugs, alloys, poisons, dyes, and glass. Much arsenic is used with lead for hardening shot.

BISMUTH

Mineral	Percentage of bismuth	Composition
Native bismuth	100.0	Bi
Bismite, bismuth ocher	[a]89.6	$Bi_2O_3 + aq$
Bismutite	79.1	$Bi_2O_3.CO_2.H_2O$
Bismuthinite	81.2	Bi_2S_3
Tetradymite	51.9	$Bi_2(Te, S)_3$

[a] Percentage of bismuth in Bi_2O_3. The water present is variable.

Native bismuth and bismuth sulphides are primary; the oxides and carbonates are secondary. Bismuth compounds are relatively insoluble and alter very slowly. In its alteration activities bismuth resembles antimony and lead.

Bismuth minerals are found in pegmatite veins and in some contact-metamorphic deposits, but the metal is derived mainly from lode ores of gold, silver, and copper. It is recovered principally from the muds obtained from refining blister copper. Although bismuth is present in small amounts in the ores of several western districts, the United States produces only a few thousand dollars' worth annually. The imports come chiefly from Germany and normally amount to about $300,000 a year. Bismuth is used for making plugs for automatic fire sprinklers, other fusible alloys, electrical fuses, solders, and glass and for toilet and medicinal preparations. The price is about $2 a pound.

Bismuth carbonate ore is mined at Engle, N. Mex.,[1] where it is associated with copper carbonates and scheelite. It has been mined also at Leadville, Colo.,[2] where it is associated with sulphides.[3] A small vein of bismuth carbonate was found in the Jelm Mountains, Albany County, Wyoming.[4] On the Mole Tableland, in northern New South Wales, bismuth ore is found in pegmatite veins.[5]

TIN

Mineral	Percentage of tin	Composition
Cassiterite	78.6	SnO_2
Stannite	27.5	Cu_2FeSnS_4

Occurrence.—Cassiterite is found sparingly in some igneous rocks and is a constituent of some pegmatites and of a few contact-metamorphic deposits. It occurs also in many veins, nearly all of which are of deep-seated origin (see page 49). In veins formed at moderate and shallow depths it is exceedingly rare. Stannite is found in many deposits in Bolivia, particularly at Potosi.[6] It is known, though rare, in some of the mines of Cornwall, England (page 234); also at Zinnwald, in the Erzgebirge, Saxony. Both stannite and cassiterite are almost insoluble in ground water; consequently tin deposits are enriched near the surface when other minerals are removed by solution. Stannite probably alters to "wood tin," or amorphous cassiterite. In some deposits the tin minerals have probably been dissolved and reprecipitated to a moderate extent, causing some

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[1] Hess, F. L.: U. S. Geol. Survey *Mineral Resources*, 1908, part 1, p. 714, 1909.

[2] Hess, F. L.: *Idem*, 1912, part 1, p. 1043, 1913.

[3] Emmons, S. F.: Geology and Mining Industry of Leadville, Colo. U. S. Geol. Survey *Mon.* 12, p. 377, 1886.

[4] Darton, N. H., Blackwelder, Eliot, and Siebenthal, C. E.: U. S. Geol. Survey *Geol. Atlas*, Laramie-Sherman folio, No. 173, p. 15, 1910.

[5] Carne, J. E.: The Tungsten Mining Industry in New South Wales. New South Wales Geol. Survey *Mineral Resources*, No. 15, pp. 68–71, 1912.

[6] Wendt, A. F.: The Potosi, Bolivia, Silver Districts. Am. Inst. Min. Eng. *Trans.*, vol. 19, p. 90, 1891.

Rumbold, W. R.: The Origin of the Bolivia Tin Deposits. *Econ. Geol.*, vol. 4, p. 321, 1909.

enrichment, but the amount of such enrichment is small compared with that in deposits of many other metals.[1]

Uses and Production.—Tin is used for plating steel, iron, and other metals, and for making tin ware, tinfoil, and bronze and other alloys. The production of tin in the United States in 1915 was 204,000 pounds, valued at $78,846. Imports, excluding tin ore, tinfoil, and other manufactures, in 1913 amounted to 53,315 short tons, valued at $46,946,756.[2] The chief sources of tin are the Malay Peninsula and the islands of Banka and Billiton, near by, where the principal deposits are placers, and the lode deposits of Bolivia and Cornwall (see page 233).

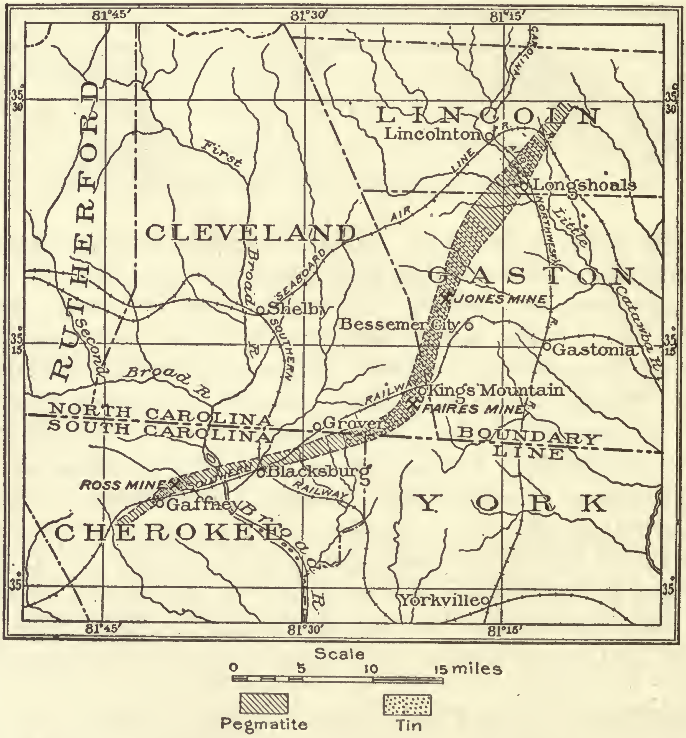

Fig. 204.—Sketch map showing distribution of pegmatite and tin in the Carolina tin belt. (*After Graton, U. S. Geol. Survey.*)

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[1] Emmons, W. H.: The Enrichment of Ore Deposits. U. S. Geol. Survey *Bull.* 625, p. 399, 1917.

[2] Hess, F. L.: U. S. Geol. Survey *Mineral Resources*, 1913, part 1, pp. 347–349, 1914.

Tin Deposits of the United States.—In the Carolina tin belt, which extends from Gaffney, S. C., nearly to Lincolntown, N. C. (Fig. 204),[1] the tin occurs in pegmatite, which is characterized by abundant muscovite, quartz, and a little plagioclase feldspar. The grade of the ore ranges from less than 1 per cent. to more than 20 per cent. The cassiterite is unevenly distributed throughout the rock. In general it is concentrated along certain lines, in the main steeply pitching in the dikes. These ore shoots are irregular and pinch and swell in an erratic manner. Some of them, however, have a considerable extent in two dimensions. The cassiterite occurs as minute grains and as bodies weighing 2 pounds or less.

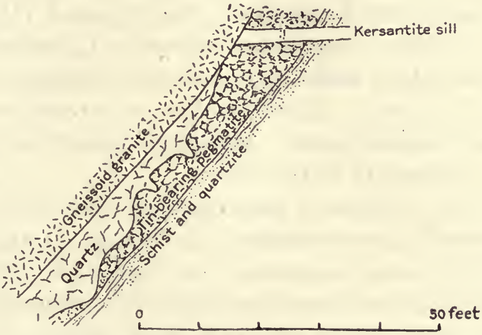

Fig. 205.—Section of tin deposit at Silver Hill, near Spokane, Washington. (*After Collier, U. S. Geol. Survey.*)

At Silver Hill, about 8 miles southeast of Spokane, Wash.,[2] cassiterite deposits are found in pegmatite veins. The area contains Ordovician schists cut by granite. The pegmatites are in the schists not far from the granite and are rudely parallel to the schistosity (see Fig. 205). The tin-bearing rock consists essentially of quartz, orthoclase feldspar, sillimanite, and andalusite. The quartz contains minute fluid and gaseous inclusions arranged in parallel lines, along many of which fractures have been developed. The cassiterite is apparently an original constituent of the pegmatite. In the principal deposit a dike

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[1] Graton, L. C.: The Carolina Tin Belt. U. S. Geol. Survey *Bull.* 260, p. 191, 1905.

[2] Collier, A. J.: Tin Ores at Spokane, Wash. U. S. Geol. Survey *Bull.* 340, pp. 295–305, 1908.

between schist and granite is followed for 125 feet down the dip of 45°. The lower part of the body is tin-bearing pegmatite; the upper part is quartz. Tin is most abundant in the central part of the pegmatite mass. The ore body locally is about 10 feet wide.

At the Etta mine, South Dakota,[1] cassiterite occurs in pegmatite. The pegmatite body is about 200 feet long and 150 feet wide. It carries huge crystals of spodumene that are mined for lithium. Associated minerals include orthoclase, muscovite, biotite, tourmaline, beryl, quartz, zircon, arsenopyrite, bismuth, and stannite.

Tin veins are found in the Franklin Mountains, Texas,[2] about 12 miles north of El Paso. In the vein quartz the oxide of tin occurs, in bunches and irregularly disseminated, intergrown with the quartz. More concentrated deposits of cassiterite occur in intimate association with the quartz and feldspar of the granite adjacent to the veins. Mineralization apparently extended only a few inches from the veins. Associated minerals are wolframite, tourmaline, fluorspar, and pyrite.

On Lost River, Seward Peninsula, Alaska, where granite intrudes limestone, a contact zone is developed, in which are found axinite, tourmaline, ludwigite, vesuvianite, fluorite, scapolite, galena, sphalerite, arsenopyrite, pyrrhotite, scheelite, cassiterite, and the ferromagnesian stannoborates hulsite and paigeite.[3] Cassiterite is found also in this region in granite and in quartz veins.

TUNGSTEN

Mineral	Percentage of WO_3	Composition
Tungstite	100.0	WO_3
Ferberite	76.3	$FeWO_4$
Wolframite	76.4	$(Fe, Mn)WO_4$
Hübnerite	76.6	$MnWO_4$
Scheelite	80.6	$CaWO_4$

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[1] Hess, F. L.: Tin, Tungsten, and Tantalum Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, pp. 131–163, 1909.

[2] Richardson, G. B.: Tin in the Franklin Mountains, Texas. U. S. Geol. Survey *Bull.* 285, pp. 146–149, 1906.

[3] Knopf, Adolph: Geology of the Seward Peninsula Tin Deposits, Alaska. U. S. Geol. Survey *Bull.* 358, p. 23, 1908.

Ferberite, wolframite, and hübnerite are probably everywhere primary. Tungstite and tungstic ocher are alteration products. Scheelite is primary in the main, but some is secondary. The tungsten minerals, like those of tin, are not very soluble in ground water and at many places accumulate in placers, along with cassiterite and other minerals that are relatively stable in the oxidizing zone. The world's largest production comes from placers in Burma.

Although the tungsten minerals are very common in pegmatites and in lodes formed at considerable depths, the most valuable deposits in the United States are lodes formed by ascending hot waters at moderate or shallow depths. At Atolia, San Bernardino County, California, in an area of schists cut by granite and granite porphyry, scheelite is found in gold-bearing quartz veins.[1] Locally in that region sands and residual surface material have been worked as dry placers. Hübnerite and wolframite placers are worked in the Little Dragoon Mountains, Arizona.[2]

In Boulder County, Colorado,[3] the principal tungsten ore is ferberite, which occurs in small veins in granite. Associated minerals are quartz, calcite, adularia, chalcopyrite, and a little galena. Precious metals, molybdenite, and tellurides are locally present. The ferberite resists weathering and forms placers. In the Black Hills[4] bedding-plane deposits of wolframite replace flat-lying calcareous beds where the latter are crossed by thin fissures. Tungsten deposits are found also in the Snake Range, eastern Nevada,[5] and in the Dillon quadrangle, Montana.[6]

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[1] Hess, F. L.: U. S. Geol. Survey *Mineral Resources*, 1909, part 1, p. 734, 1910.

[2] Rickard, Forbes: Notes on Tungsten Deposits of Arizona. *Eng. and Min. Jour.*, vol. 77, p. 268, 1904.

[3] George, R. D.: The Main Tungsten Area of Boulder, Colo. Colo. Geol. Survey *Ann. Rept.* for 1908, pp. 7–103, 1909.

Lindgren, Waldemar: Some Gold and Tungsten Deposits of Southern Colorado. *Econ. Geol.*, vol. 2, pp. 453–463, 1907.

Hess, F. L., and Schaller, W. T: Colorado Ferberite and the Wolframite Series. U. S. Geol. Survey *Bull.* 583, 1914.

[4] Irving, J. D.: Economic Resources of the Northern Black Hills. U. S. Geol. Survey *Prof. Paper* 26, p. 158, 1904.

[5] Weeks, F. B.: Tungsten Deposits in the Snake Range, White Pine County, Eastern Nevada. U. S. Geol. Survey *Bull.* 340, pp. 263–270, 1908.

[6] Winchell, A. N.: The Mining Districts of the Dillon Quadrangle, Montana, and Adjacent Areas. U. S. Geol. Survey *Bull.* 574, p. 123, 1914.

Tungsten is used for making high-speed tool steel and other alloys and electric-light filaments, for coloring glass, and for fireproofing textiles.

Tungsten minerals are recovered from tungsten ores by mechanical concentration. In 1914 the United States produced 990 tons of concentrates (contents equivalent to 60 per cent. WO_3) valued at $435,000. The production in 1915 was 2,332 tons of concentrates, valued at $4,100,000.

URANIUM AND RADIUM

Mineral	
Carnotite	$K_2O.2UO_3.V_2O_5.8(?)H_2O$
Tyuyamunite	$CaO.2UO_3.V_2O_5.8(?)H_2O$
Torbernite	$CuO.2UO_3.P_2O_5.8H_2O$
Autunite	$CaO.2UO_3.P_2O_5.8H_2O$
Uvanite	$2UO_3.3V_2O_5.15H_2O$

Pitchblende, an amorphous mineral containing uranium, rare earths, etc.

Gummite, hydrous uranium oxide with other bases.

Samarskite, of uncertain composition; contains uranium, iron, lime, and several rare earths.

Uraninite, crystalline variety of pitchblende.

Uranium minerals are found in veins associated with igneous rocks and disseminated in sandstone in regions where igneous activity is not prominent. Some of the uranium ores appear to have been deposited by cold water and enriched by superficial alteration. The uranium ores are valuable for the radium they contain. Deposits are found in Colorado and Utah. In 1915 the production of uranium, vanadium, and radium ores in the United States amounted to $693,750.

The best-known deposits of uraninite or pitchblende are in the Erzgebirge, Bohemia and Saxony,[1] and in Gilpin County, Colorado. In the Erzgebirge sedimentary and metamorphic rocks are intruded by granitic rocks. At Joachimsthal, Bohemia, the pitchblende ores are associated with quartz, dolomite, pyrite, and chalcopyrite.

At Quartz Hill, Gilpin County, Colorado, schists and granites are cut by Tertiary intrusive monzonite and bostonite porphyries. Mineralization occurred at two periods; in the first pyrite, quartz, tetrahedrite, rhodochrosite, and other minerals were formed; in

[1] Müller, Hermann: Die Erzgänge des Annaberger Bergrevieres. Erläuterung zur Specialkarte des Königreichs Sachsen, p. 66, Leipzig, 1894.

the later period the minerals were quartz, calcite, galena, sphalerite, pyrite, and chalcopyrite. Bastin[1] states that the pitchblende was deposited during the earlier pyrite mineralization and that it was subsequently fractured and veined with ores of the lead-zinc mineralization.

Uraninite, the crystallized form of the mineral which in its amorphous form is known as pitchblende, is found in pegmatites. It occurs in North and South Carolina, where it is largely altered to gummite and other minerals. Uraninite is comparatively easily attacked by weathering processes and so is almost unknown in placer deposits.

Carnotite is found at Radium Hill, near Olary, South Australia.[2] The country is an area of metamorphic gneisses and schists cut by dikes of granite and diorite. The carnotite occurs in a lode associated with quartz, biotite, magnetite, ilmenite, and rutile. As a yellow powder and small platy crystals it coats cracks and fills cavities. Crook and Blake believe that the gangue minerals are related to eruptive activity.

A vanadiferous vein which carries also a little uranium as autunite occurs 1½ miles northeast of Placerville, Colo. The district contains nearly flat sedimentary rocks, cut by intrusive diorite porphyry and by basic dikes. The deposit is in a fault fissure in the Dolores formation.[3] Near the vein the limestone wall rock is recrystallized to calcite and coated with a chromium mica. The minerals include chalcopyrite, chalcocite, autunite, asphaltum, malachite, azurite, and molybdenite. Gold and silver are also present. Near this vein are valuable bedding-plane deposits of rare metals in the overlying La Plata sandstone, which is nearly pure quartz cemented by calcite. Near the deposits the sandstone is indurated, and the calcite cement is apparently replaced by quartz. A chromium mica is deposited over extensive areas at the horizon of the vanadium ore. Secondary carnotite deposited on fractures has evidently been leached out of the vanadium ore.

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[1] Bastin, E. S.: Geology of the Pitchblende Ores of Colorado. U. S. Geol. Survey *Prof. Paper* 90, p. 1, 1914.

[2] Crook, T., and Blake, G. S.: On Carnotite and an Associated Mineral Complex from South Australia. *Mineralog. Mag.*, vol. 15, p. 271, 1910.

[3] Hess, F. L.: Notes on the Vanadium Deposits near Placerville, Colo. U. S. Geol. Survey *Bull.* 530, p. 151, 1913.

Ransome[1] considers the Placerville deposits to have replaced calcite in the sandstone. Many of them are found to give out in depth or when followed into the hills by tunnels, and, because they appear to be related to the present surface, they are supposed to have been formed or enriched by superficial agencies. Some of the carnotite deposits in La Sal Creek are pockets in sandstone above a shale, and some occupy fissures or planes of movement such as might have been formed by slipping of the sandstone on the shale since the region acquired the present topography.

Since the Placerville deposits were discovered numerous occurrences of carnotite and other nearly related minerals have been developed in rocks of the same or approximately the same age, extending over a wide area in southwestern Colorado and into Utah. All the deposits appear to be in the La Plata (Jurassic?) or the McElmo (Jurassic) formation. Fossil wood and bones are nearly everywhere associated with the deposits, and the common mineral associates are copper carbonates, vanadium and chromium minerals, and some pyrite. Hess[2] mentions a deposit in the La Sal Mountains where a petrified tree was mined for ore, the uranium being richest around the edge, or the part that was probably most decayed before burial. To account for these deposits Hess proposes a hypothesis that assumes older uranium and vanadium veins in the drainage basins that supplied the La Plata and McElmo sediments and cites several deposits as possible examples. Uranium and vanadium from these veins would be dissolved by sulphuric acid generated by pyrite and carried to the sea, where they might be precipitated by decaying reeds and trees.

VANADIUM

Vanadium in small amounts is commonly present in igneous rocks. It occurs in alteration products of many veins of copper, lead, and other metals, but its source is not known. It forms rather soluble salts and migrates readily in cold solutions. The principal ores of vanadium in the United States are carnotite, ($2U_2O_3.V_2O_5.K_2O.3H_2O$), and roscoelite, ($AlV_2.KH_2.Si_9O_{24}$).

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[1] HILLEBRAND, W. F., and RANSOME, F. L.: On Carnotite and Associated Vanadiferous Minerals in Western Colorado. U. S. Geol. Survey *Bull.* 262, p. 14, 1905.

[2] HESS, F. L.: A Hypothesis for the Origin of the Carnotites of Colorado and Utah. *Econ. Geol.*, vol. 9, p. 681, 1914.

These ores occur in sandstone in southwestern Colorado and southeastern Utah. The deposits are mentioned above as uranium and radium ores.

Near Placerville, Colo.,[1] roscoelite, together with a little carnotite, cements grains of quartz sand of the La Plata. These deposits are worked for vanadium. In this district a vein which occupies a fault[2] carries vanadium and some uranium (see page 527).

Deposits of vanadium at Minasragra, Peru,[3] are in Mesozoic sediments that are intruded by numerous dikes of eruptive rock. The principal vanadium deposit occupies a fault fissure, and the sulphide, patronite, is associated with coke and asphaltum. The carbon compounds occupy the walls and the sulphide the center of the vein. Oxidation yields green and brown oxides, which have been mined.

The principal use of vanadium is for making a special steel, to which it gives increased hardness, toughness, and power to resist shock. It is used also in making copper alloys. Vanadium salts are used as mordants in dyeing, for drugs, and in many chemical preparations. The annual production in the United States is included with that of uranium.

CADMIUM

Cadmium is not rare, but it is a comparatively unimportant metal in the arts. In the United States 91,415 pounds, valued at $108, 443, was produced in 1915. Cadmium sulphide, greenockite, is found in the Joplin region, Missouri, as a yellow powder coating crevices,[4] and the sphalerite of this region carries as much as 0.4 per cent. of cadmium. Some other zinc ores and some lead ores contain small percentages of cadmium. When zinc sulphide is heated with carbon in a retort, the cadmium comes off at a lower temperature than the zinc, and by fractional

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[1] Hillebrand, W. F., and Ransome, F. L.: On Carnotite and Associated Vanadiferous Minerals in Western Colorado. U. S. Geol. Survey *Bull.* 262, p. 14, 1905.

[2] Hess, F. L.: Notes on the Vanadium Deposits near Placerville, Colo. U. S. Geol. Survey *Bull.* 530, p. 142, 1913.

[3] Hewett, D. F.: Vanadium Deposits in Peru. Am. Inst. Min. Eng. *Trans.*, vol. 40, p. 274, 1909.

[4] Siebenthal, C. E.: U. S. Geol. Survey *Mineral Resources*, 1908, part 1, p. 793, 1909.

distillation a concentration is effected. This method is used for recovering cadmium in Germany. The cadmium produced in the United States is obtained partly from treatment of bag-house products of smelters and as a by-product in the manufacture of zinc chloride.

Metallic cadmium is used for making amalgams and alloys, and salts of cadmium are used in photography, in medicine, and in electroplating. The sulphide forms the basis of a high-grade yellow paint.

MOLYBDENUM

The principal ore of molybdenum is molybdenite (MoS_2). Other molybdenum minerals are wulfenite ($PbMoO_4$), molybdite (MoO_3), and a yellowish oxidation product, molybdic ocher[1] (a hydrous ferric molybdate). Molybdenite is primary; the other minerals named are probably everywhere alteration products.

Molybdenite, though not abundant, is widespread. It is a constituent of some igneous rocks, especially of granites, and of pegmatite veins. It occurs in both these forms at Catherine Hill[2] and near Cooper,[3] Maine. In the O K mine, Utah,[4] it is found in aplite dikes, and veins 3 or 4 inches thick are reported to occur in pegmatitic quartz. In the Santa Rita and Patagonia mountains, Arizona,[5] molybdenite is found at many places as quartz veins and impregnations in granite. Many other occurrences are described by Hess.[6]

Molybdenum is used in making hard steel and other alloys, permanent magnets and other electric apparatus, and chemicals, also for coloring porcelain green. A little molybdenum is

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[1] Schaller, W. T.: The Chemical Composition of Molybdic Ocher. *Am. Jour. Sci.*, 4th ser., vol. 23, p. 297, 1907.

[2] Emmons, W. H.: Some Ore Deposits in Maine and the Milan Mine, New Hampshire. U. S. Geol. Survey *Bull.* 432, p. 42, 1910.

[3] Smith, G. O.: Molybdenum Deposits in Eastern Maine. U. S. Geol. Survey *Bull.* 260, p. 197, 1905.

[4] Butler, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah. U. S. Geol. Survey *Prof. Paper* 80, p. 110, 1913.

[5] Schrader, F. C., and Hill, J. M.: Some Occurrences of Molybdenite in the Santa Rita and Patagonia Mountains, Arizona. U. S. Geol. Survey *Bull.* 430, p. 162, 1910.

[6] Hess, F. L.: Molybdenum. U. S. Geol. Survey *Mineral Resources*, 1908, part 1, p. 745, 1909.—Some Molybdenum Deposits of Maine, Utah, and California. U. S. Geol. Survey *Bull.* 340, p. 231, 1908.

mined in the United States; some is imported. In 1912, according to Hess,[1] the imports of molybdenum and ferromolybdenum were 3.5 tons, valued at $4,670.

SELENIUM

Selenium in small amounts is found in some gold, silver, lead, and copper ores. It is commonly associated with tellurium in ores of precious metals. Appreciable quantities are present in ores of Tonopah, Nev., Republic, Wash., and Waihi, New Zealand. Selenium is used[2] for making red gloss enamels, and glazes. Because its electric conductivity varies with the intensity of light it has many unique applications is making electric apparatus. Some selenium is obtained from the anode muds resulting from the electrolytic refining of copper. Selenium sells for about $2.50 a pound.

TELLURIUM

Tellurium, which is in the sulphur group, is closely allied also with some of the metals. It is found with native sulphur in Japan and is combined with gold, bismuth, and other metals in many vein deposits, especially in those of the late Tertiary group. In the United States it is most abundant in the gold deposits of Cripple Creek, Colo. It is generally present in small amounts in muds obtained in the electrolytic refining of copper. Tellurium is at present unimportant in the arts.

TITANIUM

The principal titanium minerals are ilmenite ($FeTiO_3$) and rutile (TiO_2). Ilmenite is a rock-making mineral and is a common constituent of titaniferous magnetite[3] which has been formed at many places by magmatic segregation (see page 343). Because of metallurgical difficulties titaniferous ores are not much used, notwithstanding the fact that titanium increases the strength of steel.

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[1] Hess, F. L.: U. S. Geol. Survey *Mineral Resources*, 1912, part 1, p. 969, 1913.

[2] Hess, F. L.: U. S. Geol. Survey *Mineral Resources*, 1908, part 1, pp. 715–717, 1909.

[3] Singewald, J. T.: The Titaniferous Iron Ores of the United States; Their Composition and Economic Value. U. S. Bur. Mines *Bull.* 64, 1913.

Rutile is found at many places in the United States and has been exploited in the Magnet Cove region of Arkansas and in Nelson County, Virginia.[1] In the Virginia region a biotite gneiss, probably pre-Cambrian, is cut by great pegmatite dikes composed of feldspar, quartz, apatite, hornblende, and rutile. The pegmatites are cut by smaller dikes composed mainly of rutile and apatite. One of these, from a few inches to 5 feet thick, may be followed for half a mile or more. Much of the rutile carries iron.

Titanium and its compounds are used for coloring various products, for hardening steel, and for electric and other purposes. In 1915 the United States produced 250 tons of rutile, valued at $27,500.

TANTALUM

The principal minerals of tantalum are tantalite ($FeTa_2O_6$) and samarskite, a complex tantalate of several rare metals. Tantalum minerals are found in pegmatite veins in the Black Hills, South Dakota,[2] and at a few places in the Appalachian region of the United States. Many foreign occurrences are known.

Tantalum has been used for filaments of incandescent lights, but tungsten has almost completely superseded it, and in 1912 no tantalum was mined. Like platinum, it is little affected by many chemical reagents, and in the future it may be used instead of platinum to some extent in chemical laboratories. The price was 59.4 cents per gram in 1912.

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[1] WATSON, T. L.: The Occurrence of Rutile in Virginia. *Econ. Geol.*, vol. 2, p. 493, 1907.

[2] HESS, F. L.: Tin, Tungsten, and Tantalum Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, pp. 131–163, 1909; U. S. Geol. Survey *Mineral Resources*, 1908 and later years.

CHAPTER XXVIII

DEPOSITS OF THE NONMETALS

BUILDING STONES

Granite, sandstone, limestone, marble, slate, and many other rocks are used for building and for ornamental purposes. To be desirable for such uses a stone should have a pleasing color, satisfactory structure, strength, durability, and uniform texture, and for use in a moist country it should have low porosity. The color is of course a matter of taste and fashion. At present the lighter shades are more desirable than the darker ones. Most stone used in the main courses of buildings has strength far beyond that required of it, but if the stone is to be used for window caps or near other openings where stresses are unequal, its strength must be ascertained more carefully. Blocks near doors and windows, sill blocks, and caps are frequently broken in buildings. Strength tests are made by measuring the force necessary to crush a block of stone in a testing machine. Tests of transverse strength—that is, strength to withstand pressure applied unequally at different places—are made by supporting the two ends of a bar of stone and applying a force between the two supports.

Durability depends on several qualities. In general, fine-textured rocks, especially sandstone and marble, are more durable than coarse-textured rocks, although this is not universally true. Certain minerals are undesirable for building stone—particularly pyrite and other iron sulphides, because they oxidize, staining the rock yellow, and as they are soluble the surface becomes pitted. Moreover, sulphuric acid formed by oxidation dissolves the stone, especially limestone. Nearly all igneous rocks and many sedimentary rocks contain some pyrite. A little, say about 0.3 per cent., if disseminated in the rock is not objectionable, but if it is concentrated in seams and veinlets it oxidizes and weakens the structure.

Mica is considered undesirable when it forms nodules and bunches in granite, because it renders the stone unsightly. In some quarries mica "knots" cause considerable waste. Small amounts of mica disseminated in the rocks are not injurious nor undesirable. Mica schists have been used very effectively in certain cities to produce the rough surfaces that are preferred by some. In marble, chert is injurious because it is cut and polished with more difficulty than the calcite, and moreover its presence causes the limestone to weather unevenly.

Freezing and thawing tests are sometimes made. The stone is soaked in water and the effects of freezing noted. Instead of water, a saturated sodium sulphate solution is sometimes used to simulate the effect of freezing by crystallization of the sulphate in the rock pores. The value of this test, however, has been questioned. Absorption tests also have value for rocks to be used in structures exposed to water, and heat tests for rocks exposed to fire.[1]

Aside from the laboratory tests, valuable information may be obtained by studying a stone in the quarry and noting the effects of weathering on it, and also by studying the effects of weathering on buildings of known age. There is a great difference in the durability of stones. Some will weather badly in less than 20 years; others endure for centuries.

Chemical analyses are not especially valuable for showing the desirability of a stone for building. Microscopic examinations are sometimes useful, as they disclose the minerals contained in the rock. It is more important to ascertain the larger structural features, particularly the bedding, jointing, and sheeting. Many quarries are profitable because the joint systems are favorably spaced. For monoliths there should be but two systems of joints spaced fairly far apart. For paving blocks closely spaced sheeting is desirable. Joint systems that make angles of 45° or less with other systems are highly undesirable, for they break the rocks into sharp wedges that must be trimmed.

A plane along which a granite may be easily broken is called the rift. Some rocks that appear to be perfectly homogeneous are found to be more readily broken in one direction than in others. When such planes lie in two directions, one is frequently called the rift and the other the run or grain of the rock. Such

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[1] McCourt, W. E.: Fire Tests of Some New York Building Stones. N. Y. State Mus. *Bull.* 100, pp. 1–36, 1906.

planes are probably incipient fracture planes, but they are as yet little understood.

In considering the opening of a quarry, aside from the quality of the stone, cost of operation is an important factor. It is determined in part by the jointing, bedding, and other features mentioned above. The demand for the stone, the character of competing quarries, transportation facilities, and freight rates also are obviously to be considered. The quarry should have sufficient material available so that its product once established in the market may be supplied through a period of years. Among undesirable features in granite are knots, inclusions, dikes, hair lines (small dikes of dark rocks), quartz veins, pegmatite areas, pyrite lumps, and sheeting too closely spaced. Objectionable features in sandstone and limestone are clay seams too closely spaced, too much clay in the rock, shattered zones, pyrite areas, and mica bands. The building stone produced in the United States in 1915 was valued at $74,595,352.

An adequate presentation of the distribution of building stone in the United States would involve a discussion of the regional geology of the whole country, a subject too extensive to be included in this volume. General papers with bibliographies are mentioned below.[1]

SLATE

When mud and clay are deeply buried and subjected to pressure, they generally assume a slaty cleavage by virtue of which they may be separated into thin, tough plates. These plates are commercially termed slates and are utilized for roofing, stair treads, wainscoting, laboratory tables, etc. When a clay is changed to slate by pressure or dynamic metamorphism, the stable minerals like quartz are rearranged so that the long dimen-

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[1] Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1909–1912.

Ries, Heinrich, and Watson, T. L.: "Engineering Geology," pp. 490–492, New York, 1913.

Merrill, G. P.: "Stones for Building and Decoration," New York, 1903.

Eckel, E. C.: "Building Stones and Clays," New York, 1912.

Ries, Heinrich: "Building Stones and Clay Products," New York, 1912.

Buckley, E. R., and Buehler, H. A.: The Quarrying Industry of Missouri. Mo. Bur. Geol. and Mines, 2d ser., vol. 2, 1904.

Buckley, E. R.: On the Building and Ornamental Stones of Wisconsin. Wis. Geol. and Nat. Hist. Survey *Bull.* 4, 1898.

sions of the particles lie in one plane, and new minerals such as actinolite, tremolite, mica, and chlorite, developed from kaolin and other minerals in the clay, will form with their long axes in the same plane as the long dimensions of the mineral fragments (see page 116). The slate will split most readily along such a plane. Igneous tuffs and other material of igneous origin may also be changed by dynamic metamorphism into slaty rocks, but nearly all the commercial slates are of sedimentary origin.

Slates are black, green, gray, or red, their color depending on that of the constituent minerals. Some slates change color on long exposure, particularly many green slates, which become bleached, and many red slates, which tend to become brown. Black slates and gray slates are generally more nearly permanent in color. Moderate bleaching is not very objectionable unless the slate becomes spotted. For roofing, a slate should be of nearly permanent color and should not break on being punched. Lime carbonate, iron carbonate, and pyrite are objectionable constituents.

Slates are formed in areas where the rocks have been subjected to dynamic metamorphism. They are found in the Appalachian region from Maine to Alabama. Beds that are but little worked occur in Michigan, in Minnesota, and in the western Cordillera. The value of the slate produced in the United States in 1915 was $4,958,915.

References to general papers that contain bibliographies are given below.[1]

CLAY

Clay is a term used without any very definite mineralogic significance to define material that is plastic when wet and that when shaped and dried will retain its shape and when burned will become hard. The principal constituent of most clays is kaolinite, $H_4Al_2Si_2O_9$, or a colloid of approximately similar composition, but fragments of quartz, iron oxides, silicates, and other minerals are generally present. Kaolin is the commonest product of

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[1] Dale, T. N.: Slate Deposits and Slate Industry of the United States. U. S. Geol. Survey *Bull.* 275, 1906.

Dale, T. N., and others: Slate in the United States. U. S. Geol. Survey *Bull.* 586, 1914.

Eckel, E. C.: "Building Stones and Clays," pp. 95–126, New York, 1912.

Ries, Heinrich: "Building Stones and Clay Products," New York, 1912.

weathering of aluminum minerals such as feldspars and micas. Nearly all igneous rocks contain aluminum minerals, and kaolin is almost invariably formed as a result of their weathering. Thorough weathering of feldspar-bearing pegmatites may yield high-grade kaolin deposits. Limestones also generally contain aluminum as kaolinite and by weathering form residual clays. Shales are clays that have been consolidated by pressure. On weathering they break down and again form clays. If a surface has long been exposed to weathering with little erosion, as happens when a region approaches base-level, soluble substances are almost completely leached out, and the residual clay remains. Ordinarily the parent rock may be found a few feet or rarely more than 50 or 100 feet below the surface. Such clayey substance or mantle rock commonly constitutes the soil of old unglaciated surfaces. Even sandstone and quartzite contain some clay, and their residual soils may be more aluminous than the parent sandy rocks.

In normal erosion much of the weathered clayey material is carried by streams and deposited along rivers or in deltas. Through uplift or rejuvenation clay terraces may form. Where a weathered surface is rejuvenated, erosion of the upland is more rapid, and more clayey material is deposited.

Glacial till generally contains much clay, and where the till is worked over and sorted by glacial waters, clay deposits of considerable magnitude are commonly formed. Such deposits usually differ from residual clays in that they contain "rock flour," or material derived from the mechanical abrasion of rocks and not by weathering, which removes the more soluble constituents of rocks. Many glacial clays contain considerable lime carbonate and effervesce freely with acid.

The plasticity of clays is probably due to colloidal substances or "gels" that they contain. Halloysite and pholerite, colloidal aluminum silicates more highly hydrated than kaolin, are probably present in most clays and doubtless are important in connection with plasticity.[1] Grout[2] believes that molecular attraction also plays a part in rendering clays plastic.

Analyses of clays do not go very far to show their availability.

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[1] Cushman, A. S.: On the Cause of the Cementing Value of Rock Powders and the Plasticity of Clays. Am. Chem. Soc. *Jour.*, vol. 25, pp. 451–468, 1903.

[2] Grout, F. F.: The Plasticity of Clays. *Idem*, vol. 27, p. 1037, 1905.

Kaolin contains silica, 46.5 per cent.; aluminum, 39.5 per cent.; and water, 14 per cent.; but few clays approach kaolin closely in composition. The china clays and fire clays are nearest to kaolin; as a rule they result from weathering of feldspathic igneous rocks or of sedimentary rocks. Alkalies, lime, magnesium, and iron lower the fusing points of clays and render them useless as refractory material.

Burning tests are the most satisfactory tests of clays. Iron in clay on burning colors the brick red. It is counteracted by lime carbonate. Many glacial clays—for example, those of Milwaukee, Wis.—burn buff, owing to excess of lime. Too much lime, however, is undesirable, and limestone pebbles will cause the brick to crumble. Too much carbonaceous matter is also undesirable, as it causes bloating. Silica lowers shrinkage and plasticity. Sand may be added to clay where less fire shrinkage is desirable.

Fire clays are formed where the physiographic conditions are favorable for the leaching out of all materials other than kaolinite. Such conditions may exist where coal beds are formed. The ground waters, aided by vegetation, remove the more soluble substances. Thus fire clay is commonly found below a bed of coal. At some places in the Missouri and Illinois coal fields the bed of fire clay is removed and the coal is left as a support for the overlying material.

Aside from the residual clays and the sedimentary and glacial clays, loess, a wind-blown material, is used at many places for brickmaking.

In making brick, the following changes take place. The molded material is dried, with some shrinkage. On firing there is further shrinkage, the total decrease in volume commonly amounting to 10 per cent. or more. Combined water is driven off at about 450° C., and any organic matter will undergo combustion at temperatures somewhat higher. As the temperature is raised iron is oxidized, and if enough iron is present the brick becomes red. If carbonates are present carbon dioxide escapes. Incipient fusion takes place, and this hardens the mass. If the temperature is raised high enough the brick is vitrified, particularly the outer surface, which is hottest.

In the United States nearly every State has large supplies of clays. In the Coastal Plain region from New York south and along the Atlantic and Gulf coast to Texas transported clays are abundant. They are coast deposits later elevated above the water level. In the glaciated regions glacial clays abound. In the southern Appalachians and at some other places in the unglaciated regions residual clays are found. Shales and slates that represent clay beds of past geologic ages are also used at many places. The raw clay produced in the United States in 1915 amounted to 2,362,954 tons, valued at $3,971,941. The clay products of 1915 were valued at $163,120,232.

The uses of clays and clay products are well known.

Discussions of the technology of clays and descriptions of occurrences are given in the papers cited below.[1]

FULLER'S EARTH

Fuller's earth is a clayey material used for cleaning grease from cloth and for refining petroleum oils and other fluids by filtration. Like clay, it is a product of weathering or of weathering and sedimentation. It differs from clay, however, in that it has low plasticity. Its water content is high. Chemical analyses are of little aid in determining whether a clay will serve as fuller's earth. Tests for the purposes for which it is intended to be used give the only trustworthy evidence. In 1915, the deposits worked in the United States yielded 47,901 short tons of fuller's earth, valued at $489,219, and the imports amounted to $143,594.[2] The demand for fuller's earth is good. The largest quantity is obtained in Florida and Georgia, where it is quarried from Oligocene beds. In Arkansas it is derived from weathered basic

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[1] Ries, Heinrich: The Clays of the United States East of the Mississippi River. U. S. Geol. Survey *Prof. Paper* 11, 1903. "Clays: Occurrence, Properties, and Uses," New York, 1908.

Merrill, G. P.: "Rocks, Rock Weathering, and Soils," New York, 1906.

Eckel, E. C.: "Building Stones and Clays," New York, 1912.

The technology and uses of clays, especially those of glacial origin, are summarized in *Bull.* 11 of the Minnesota Geological Survey, by F. F. Grout and E. K. Soper. A complete list of papers on clays would be too long for this volume. Bibliographies will be found in the volumes by Ries, Merrill, and Eckel, noted above; also in one by J. C. Branner (Bibliography of Clays and the Ceramic Arts. U. S. Geol. Survey *Bull.* 143, 1896). Eckel (*op. cit.*, p. 236) gives also a list of references on origin.

[2] Middleton, Jefferson: U. S. Geol. Survey *Mineral Resources*, 1915, part 2, pp. 10-12, 1916.

rocks. Papers treating deposits of fuller's earth in the United States are cited below.[1]

FELDSPAR

Occurrences of feldspar are mentioned on pages 18–28. The feldspar utilized in the arts is obtained exclusively from pegmatite veins and deposits formed by magmatic segregation. The principal use is for making pottery, glass, porcelain, enamel brick, and other enamel ware. Potash, soda, and lime feldspars are utilized. Much of the feldspar marketed contains 10 to 20 per cent. of quartz. Because the hardness of feldspar is less than that of quartz, it will not so readily scratch glass and consequently there is a demand for quartz-free feldspar for window wash and polishing powder. The production of feldspar in the United States in 1915 was 113,769 short tons, valued at $629,356. Nearly all of this was obtained in the New England States and the southern Appalachian region. California also produces considerable feldspar.[2]

MICA

Although mica is a common constituent of igneous rocks, of crystalline schists, of contact-metamorphic deposits and of some

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[1] Alden, W. C.: Fuller's Earth and Brick Clays near Clinton, Mass. U. S. Geol. Survey *Bull.* 430, pp. 402–404, 1910.

Day, D. T.: The Occurrence of Fuller's Earth in the United States. Franklin Inst. *Jour.*, pp. 214–223, 1900.

Merrill, G. P.: "The Nonmetallic Minerals," pp. 248–250, New York, 1904.

Miser, H. D.: Developed Deposits of Fuller's Earth in Arkansas. U. S. Geol. Survey *Bull.* 530, pp. 207–219, 1912.

Parsons, C. L.: Fuller's Earth. U. S. Bur. Mines *Bull.* 71, pp. 1–38, 1913.

Porter, J. T.: Properties and Tests of Fuller's Earth. U. S. Geol. Survey *Bull.* 315, pp. 268–290, 1907.

Ries, Heinrich: "Clays, Their Occurrence, Properties, and Uses," pp. 460–467, New York, 1906.

Vaughan, T. W.: Fuller's Earth of Florida and Georgia. U. S. Geol. Survey *Bull.* 213, pp. 392–399, 1903.

[2] The bibliography of feldspar deposits of the United States is extensive. Citations under "Quartz" (page 551) refer also to feldspar. The principal deposits are discussed by Bastin, E. S.: Economic Geology of the Feldspar Deposits of the United States. U. S. Geol. Survey *Bull.* 420, pp. 1–85, 1910.

veins, the mica of commerce is derived from pegmatites. Most pegmatites are composed chiefly of quartz, feldspar and mica. In the commonest type feldspar predominates, but in some pegmatites quartz is the principal constituent, and in a few mica is abundant. The micas[1] include muscovite ($H_2KAl_3Si_3O_{12}$), phlogopite ($H_2KAlMg_3Si_3O_{12}$), and biotite ($HKAl_2Mg_2Si_3O_{12}$). Iron also is commonly present in biotite, taking the place of aluminum or magnesium. Lepidolite, or lithium mica, is a source of lithium salts. The important commercial micas are muscovite and phlogopite.

The larger pieces of mica are used for glazing stoves and lamp chimneys and in making electric apparatus. Smaller pieces are used in making "micanite" or built-up mica board, used chiefly for electric appliances. In making dynamos mica is used as an insulator; phlogopite is preferred for such use, as it wears more uniformly than muscovite and does not cause the machine to spark. Sterrett states that black specks or magnetite dendrites in mica do not impair its insulating quality. Ground mica is used for making paints, wall paper, lubricants, building paper, etc. The United States in 1915 produced 553,821 pounds of trimmed mica, valued at $378,259, and 3,959 tons of scrap mica, valued at $50,510. Large clear pieces of mica cut to dimensions of several inches square sell for $1 a pound or more, but low-grade material is cheap.

The mica produced in the United[2] States comes from New England,[3] the southern Appalachian region,[4] the Black Hills, South Dakota,[5] and Colorado. The imports are mainly from Canada[6] and from Ceylon.

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[1] STERRETT, D. B.: Mica. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, p. 1130, 1912 (includes bibliography).

[2] HOLMES, J. A.: Mica Deposits in the United States. U. S. Geol. Survey *Twentieth Ann. Rept.*, part 6 (continued), pp. 691–707, 1899.

[3] RICE, C. F.: Description of Mica-Mining Company in Grafton County, New Hampshire. *Min. and Sci. Press*, Feb. 23, 1901.

[4] STERRETT, D. B.: Mica Deposits of North Carolina. U. S. Geol. Survey *Bull.* 430, pp. 593–638, 1910.

PRATT, J. H.: The Mining Industry in North Carolina (an annual publication of the North Carolina Geol. Survey), 1900–1910.

[5] STERRETT, D. B.: Mica Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, pp. 382–397, 1906.

[6] ELLS, R. W.: Mica Deposits of Canada. Canada Geol. Survey *Pub.* 869, 1904.

LITHIUM MINERALS

Lithium is obtained principally from lepidolite (lithium mica), spodumene, and amblygonite. Lithium minerals are exploited in San Diego County, California, and in the Etta mine, in the southern Black Hills.[1] Smaller amounts are found at Paris, Maine, and at many other places in New England. Bodies of these minerals of commercial size are practically confined to pegmatite veins (see page 25). Only a few hundred tons of lithium minerals are produced annually in the United States. The prices range from $10 to $40 a ton. The material is normally exported to Germany, where soluble lithium salts are made from the silicates. Lithium salts are used in medicine and in medicinal waters.

CEMENTS AND LIMES

Cement.—Cement[2] is made by fusing mixtures of oxides of calcium, aluminum, and silicon. When the clinker is ground and mixed with water it sets to a strong, hard, solid mass. The three oxides need not be present in exact proportions, but within certain limits the mixture may vary. Some limestones containing considerable clay are of suitable composition for cement without the addition of other material. The cements made of such limestones are termed natural cements. If the mixture is made artificially it is called Portland cement. The hardening is not brought about by the addition of material from the atmosphere, as when mortar hardens by the addition of CO_2, but is due to the formation of hydrates of calcium and aluminum. Portland cement and some natural cements will harden under water as well as in air.

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[1] Hess, F. L.: Tin, Tungsten, and Tantalum Deposits of South Dakota. U. S. Geol. Survey *Bull.* 380, pp. 159–161, 1909; U. S. Geol. Survey *Mineral Resources*, 1909, part 2, p. 649, 1910.

[2] Eckel, E. C.: Portland Cement Materials and Industry in the United States. U. S. Geol. Survey *Bull.* 522, 1913.—"Limes, Mortars, and Cements," New York, 1907.

Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 485–515, 1912.

Ries, Heinrich, and Eckel, E. C.: Lime and Cement Industries of New York. N. Y. State Mus. *Bull.* 44, 1901.

Bleininger, A. V.: The Manufacture of Hydraulic Cements. Ohio Geol. Survey *Bull.* 3, 1905.

Rankin, G. A., and Wright, F. E.: The Ternary System $CaO–Al_2O_3–SiO_2$. *Am. Jour. Sci.*, 4th ser., vol. 39, pp. 1–79, 1915.

Analyses of calcareous rock to be used for natural cements should show between 15 and 40 per cent. of clay and silica and not more than a small percentage of magnesia. After burning only a small percentage of free lime should be present.

Portland cement is made by mixing a calcareous material, such as limestone, chalk, or marl, with a siliceous and aluminous material, such as clay, shale, slag, or mud. As it is possible to vary the proportions of the substances used the mixture is made to approach closely a desirable standard composition that has been found satisfactory by previous experimentation. Portland cement is generally superior to most natural cements, because the mixture is more easily controlled and is nearly uniform. The mixture before burning generally consists of about 75 per cent. $CaCO_3$, not more than 5 per cent. $MgCO_3$, 12 to 15 per cent. SiO_2, and 4 to 7 per cent. Al_2O_3. Between 1 and 2 per cent. of Fe_2O_3, K_2O, and organic matter are commonly present. None of these substances are detrimental except MgO, which, if running above 6 per cent., at least under some conditions, will weaken the product. Iron oxide and potassium oxide, on the other hand, are desirable, for they lower the temperature necessary for sintering. On burning CO_2 and H_2O are driven off, and the percentages of other substances in the clinker are thereby increased about one-half.

Cement making consists of three steps—(1) grinding and mixing, (2) clinkering, (3) grinding the clinker.

In grinding, chert and other siliceous matter in the limestone are generally considered undesirable, as they increase the cost. Recently improvements in grinding machines have reduced the cost of grinding, and there is an increasing tendency to utilize the purer limestone and the slags, instead of softer marl and argillaceous limestone. In burning the cement mixtures, the temperatures employed are generally above 1500°F., depending on the composition of the mixture and the nature of the burning apparatus. The mixture contains considerable CO_2 in carbonates, and this is driven off at about 750°F. to 1400°F., increasing porosity and decreasing volume of material. In burning complete fusion is avoided, for on fusion the constituents might segregate. Incineration is accomplished, therefore, not in a shaft like those employed in smelting the metals, but, in many plants, in long revolving cylinders, tilted a little so that the material moves automatically from the intake at the upper end to the point of discharge at the lower end. Flame, generally kindled by powdered coal or oil, is introduced at the lower end and escapes at the upper end of the cylinder through a flue provided there. The burner resembles the Howell-White dryer formerly used extensively in the West in silver mills, but in general the temperatures employed are higher and the cement kilns are much larger, some of them being 240 feet long.

The clinker, which comes out as small masses, is ground in ball mills. Fine grinding is necessary, as cement that is not finely ground will not set.

Natural cement is made by burning impure limestone containing 15 to 40 per cent. silica, alumina, and iron oxide. The temperature required is not much above that at which lime is burned, and kilns like the ordinary limekilns may be used. Carbon dioxide is driven off, and lime silicates, aluminates, and ferrates are formed. The ground clinker does not slake and sets slowly under water.

The production of cement in the United States in 1915 was 87,685,222 barrels, valued at $75,155,102.

Mortar.—The function of a mortar is to act as a binding material, converting the blocks of a wall or other structure into a coherent mass. It is made by mixing from 1 to 5 parts of clean sand with 1 part of slaked lime or cement. Generally cement is considered more durable for buildings, and in some that are centuries old it still endures.

Concrete.—Concrete is a mixture of sand, cement, and gravel or crushed stone, in which the cement acts as a mortar. Because the material can be poured into forms and thus handled cheaply, its use is rapidly increasing. The principle that the total pore space in a rock depends not on the size of particles but upon uniformity of size, being greatest when particles are of equal size (see page 172), is important in this connection. So long as the cement makes into a coherent mass the various particles, the less required the better, provided the other materials used in the concrete mixture are sufficiently strong. In the larger concrete structures it is considered desirable to introduce large irregular blocks of stone, which generally decrease cost and increase strength. Even in neat cement not all of the mixture becomes hydrated to form new compounds, but the small part that does is sufficient to bind the other parts together firmly. Sand is sometimes ground fine and added to cement. It should not be regarded as an adulterant, because a small amount may even add to the strength of the product, especially if the sand grains are angular and thus interlock and present large surfaces of contact.

Lime.—Lime is made by heating limestone to about 800°. Impure limestones are heated to a higher temperature. At such temperatures the limestone loses CO_2 and becomes "quicklime," CaO. When water is poured on quicklime chemical action takes place: $CaO + H_2O = Ca(OH)_2$. This reaction increases volume: about 32 parts of water is added to 100 parts CaO. As calcium hydroxide is somewhat soluble it is used extensively in the arts to neutralize acids and to make solutions alkaline. Large amounts are used in sugar refining, in cyaniding gold ores, and in tanning. Quicklime is used in the manufacture of alkalies and bleaching powders, etc. It is the cheapest alkali, just as sulphuric acid is the cheapest acid, and it has a correspondingly important position in the arts.

Common lime mortar is made by mixing sand, quicklime, and water. It is hardened by CO_2 of the air:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

A crust first forms, enough to hold the bricks or stones, and very slowly the carbonation extends inward. The calcite crystals form only a matrix or "groundmass" for the particles of sand, just as hydrates form the matrix in Portland cement mixtures. The sand adds strength and decreases shrinkage; without sand, cracks will form on drying. Lime mortar does not harden in damp places, and its use is not recommended for cellars and deep foundations. Calcium carbonate, if nearly pure makes a lime that slakes readily ("fat lime"). If magnesia is present it slakes more slowly (meager or cold lime). This is not always undesirable, and more magnesium is allowable than in limestone to be used for making Portland cement. For many structural purposes magnesian lime is preferable. Some lime is hydrated, dried, and powdered before being marketed.

With increasing alumina and silica lime grades into natural cement. Some argillaceous limestones, heated somewhat above the point of decarbonation, yield bricklaying cement that is said to be superior to common lime for making mortar.

Puzzolan Cement.—Puzzolan cement is made by mixing slaked lime with finely ground clayey material, finely ground furnace slag, or volcanic ash. It is not calcined, and the mixture is little more than a lime mortar. The material is cheap but is not recommended for structures intended to endure, although in Italy some houses made of such material have had a long life. Puzzolan cement should not be confused with Portland cement made of slags from iron blast furnaces. In making Portland cement from slags, the slags are ground and other material is added to give a suitable mixture. After sintering the clinker is ground as in making Portland cement from other materials.

Distribution of Materials.—In 1911, according to Burchard, mixtures of argillaceous limestone and pure limestone supplied material for 34.1 per cent. of the Portland cement product of the United States; limestone and clay or shale, 51.8 per cent.; marl and clay, 4.2 per cent.; and slag and limestone, 9.9 per cent.

It is desirable that limestone to be used for making Portland cement should be nearly homogeneous in composition, for then the composition of mixtures may be very easily controlled. At some places, however, the beds that are used show considerable variation in composition, both along and across the strike. Magnesian beds, or those containing too much clay, are avoided, or when they are used purer limestone is added. A limestone with some clay is preferable to a pure limestone if the clay is evenly distributed, because it simplifies mixing.

Limestones suitable for making Portland cement are widely distributed in the United States; detailed accounts of their distribution are given in papers by Burchard[1] and Eckel.[2] The Lehigh Valley district of Pennsylvania[3] is the principal source. It supplied in 1910 about one-third of the product of the United States. The rocks are of Paleozoic age and are closely folded. The Trenton limestone and Hudson River shale supply much of the cement material. The lower part of the Trenton is nearly pure limestone but contains some dolomite beds that are avoided as far as practicable in quarrying. The upper part of the Trenton is argillaceous limestone, some of which has the composition of natural cement rock. Mixtures of the lower and upper beds provide a material of suitable composition. The

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[1] Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1910, part 2, pp. 489–526, 1911.

[2] Eckel, E. C.: "Limes, Mortars, and Cements," New York, 1907.

[3] Peck, F. B.: Geology of the Cement Belt in Lehigh and Northampton Counties, Pennsylvania. *Econ. Geol.*, vol. 3, pp. 37–76, 1909.

Lehigh belt of Trenton limestone extends into New Jersey, where also this formation supplies much material for cement.

In eastern New York Portland cement is made of Ordovician and Silurian limestones mixed with surface clay. In Kansas Mississippian, Pennsylvanian, Permian, and Cretaceous limestones are used. In Texas and Arkansas Cretaceous shales and limestones supply material for Portland cement. Devonian beds are used in Kentucky, Ohio, and Wisconsin. In the glacial belt, especially in Michigan, Indiana, and Ohio, fresh-water marls are used with Pleistocene clays. The marl forms in the lakes through the agency of small plants, especially the stonewort, *Chara.*[1] It is commonly incoherent and in some lakes is pumped out and dried for cement making. Some of the lakes are drained, and the partly dried marl is excavated with steam shovels.

Rocks for natural cement are quarried from the Silurian beds in Ulster, Schoharie, Erie, and Onondaga counties, New York. Natural cement rocks are obtained also in Maryland and Virginia, at Utica, Ill., near Milwaukee, Wis., and Mankato, Minn., and at several other localities.

LIME SOLD IN THE UNITED STATES IN 1915, AND USES[a]

	Quantity (short tons)	Value	Average per ton
Building lime	1,136,696	$4,812,710	$4.23
Chemical works	492,870	1,653,750	3.36
Paper mills	216,819	782,396	3.61
Sugar factories	34,025	230,368	6.77
Tanneries	47,104	190,864	4.06
Fertilizer	653,686	2,163,874	3.31
Dealers—uses not specified	595,128	2,508,907	4.22
Other uses[b]	413,371	1,993,887	4.82
	3,589,699	14,336,756	3.99

[a] LOUGHLIN, G. F.: U. S. Geol. Survey *Mineral Resources*, 1915, part 2. p. 245, 1916.

[b] Includes lime for sand-lime brick, slag cement, alkali works, steelworks, glassworks, smelters, shep dip, disinfectant, manufacture of soap, cyanide plants, glue factories, purification of water, etc.

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[1] DAVIS, C. E.: A Contribution to the Natural History of Marl. *Jour. Geol.*, vol. 8, pp. 485–497, 1900; vol. 9, pp. 491–506, 1901.

Limestones suitable for lime are widely distributed. In a search for deposits of limestone to supply lime or cement for a certain market it is advisable to consult geologic maps of regions near by[1] and ascertain the lithologic character of the formations. Analyses will show what beds are available. Some hundreds of analyses of limestones quarried in the United States are recorded by Burchard.[2]

NATURAL ABRASIVES

Many minerals and rocks are used in their natural state as abrasives. These include sandstone, grit, chert, garnet, corundum, emery, quartz, feldspar, infusorial (diatomaceous) earth, tripoli, pumice, etc.

Millstones are shaped from grit and sandstone. They are manufactured in several States, especially in New York and Virginia. Formerly they were in considerable demand, and in 1880[3] the production in the United States was valued at $200,000. In 1915, however, the total was only $53,480. In recent years the use of steel rolls and ball mills for grinding has caused a marked decrease in the demand for millstones.

Grindstones also are shaped from grit or sandstone. They are used mainly to sharpen steel tools. The grain should be fairly uniform and the particles cemented firmly, yet the pore space should not be entirely filled with cement so that cutting edges are buried. Too much clay in the sandstone will cause a smooth surface to form on grinding, and that will impair cutting efficiency. Certain layers of the Berea grit of Ohio and Michigan are extensively used for grindstones.

Pulpstones are large grindstones used for grinding wood to paper pulp. The wood is softened by introducing steam in a jacket around the circular pulpstone, and the pulpstone must have a cement that does not disintegrate in the presence of steam. Most of the pulpstones used in the United States come from England. Some of the stones are 5 feet or more in diameter and weigh over 2 tons. Experiments have been made to utilize

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[1] Willis, Bailey: Index to the Stratigraphy of North America. U. S. Geol. Survey *Prof. Paper* 71, 1912 (contains extensive references).

[2] Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 658–680, 1912.

[3] Phalen, W. C.: Abrasive Materials. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, p. 837, 1912.

sand and cement to make artificial pulpstones, so as to avoid the expense of shaping.

Scythestones, whetstones, and oilstones are small abrasive stones generally used as hand tools. They are made from rocks of varied character, but mainly from sandy sedimentary rocks and schists. The novaculite (hard) and Wachita (soft) stones of southwestern Arkansas are noteworthy. Both of these stones are nearly pure silica. They are found as thin beds in a folded series of sandstones and shale. The hard Arkansas stone is very dense and has but small pore space; it is much prized as a finisher of razors and other fine instruments. The soft Arkansas stone has much greater abrasive power on account of its greater pore space, but it does not produce so fine an edge.

Volcanic "ash" is volcanic matter in a very finely divided state. It is used for polishing and for making scouring soaps. It is common in many Western States and is mined in Nebraska.[1] Pumice is a solidified rock froth formed of rock material by gases escaping from lavas and having in general about the composition of rhyolite. It has many domestic uses. Ground pumice resembles volcanic ash. The United States in 1915 produced 27,708 tons of pumice and volcanic ash, valued at $63,185, principally from Nebraska and Kansas. The pumice blocks of commerce come mainly from Lipari, an island north of Sicily. Deposits are known in the western part of the United States, but apparently they can not compete with those of Italy, where labor is cheaper.

Tripoli is a fine, nearly pure silica, that is found in siliceous limestone in Missouri and Illinois. It is ground and sold for abrasive dust and is used also for wood filler.

Garnet is extensively used as an abrasive, particularly the varieties almandine, pyrope, and grossularite. The garnets used for this purpose are obtained from schists in New York, New Hampshire, and North Carolina. Considerable garnet is used in the manufacture of sandpaper, and for certain purposes it is superior to quartz.

Corundum (Al_2O_3) is one of the hardest minerals, standing at 9 on the Mohs scale. Its powder is used for grinding, and small crystals are used for watch jewels. It is found in certain igneous

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[1] Barbour, E. H.: Pumice. Nebr. Geol. Survey, vol. 1, pp. 214–220, 1903.

rocks that are rich in aluminum and poor in silica. Corundum occurs also in nepheline syenite,[1] schist, and pegmatite and in gravel formed by the waste of corundum rocks. Corundum is found at many places in the crystalline schist belts of the Appalachian region. Pratt[2] has shown that some of the corundum ores are derived from dunite by segregation.

Emery is a mixture of hematite and corundum, and some of it contains other minerals. The ground powder is sized and used for polishing and for making sandpaper. It is mined in small quantities in the Appalachian region. Ground quartz also is used for making sandpaper.

Feldspar, which is softer than quartz, is ground and used for polishing powder, especially to polish glass and other materials where scratching is to be avoided. Diamonds are used as dust and uncut in bits of core drills. Chromic oxide and rouge (hematite powder) are used for fine polishing. The natural abrasives must compete more and more with the artificial abrasives, especially with carborundum (CSi) and alundum (Al_2O_3). Both of these are made in electric furnaces.

VALUE OF NATURAL ABRASIVES[3] PRODUCED AND MARKETED IN THE UNITED STATES, 1915[4]

Millstones	$53,480	Garnet	139,584
Grindstones and pulpstones	648,479	Diatomaceous (infusorial) earth and tripoli	611,021
Oilstones and scythestones	115,175	Pumice[5]	63,185
Emery	31,131		
			1,662,055

INFUSORIAL (DIATOMACEOUS) EARTH

Minute organisms such as diatoms and radiolaria—extract silica from water, and their tests accumulate in great abundance in some places at the bottoms of ponds, lakes, and in the sea. This material when pure is very light and fluffy, and as it contains

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[1] ADAMS, F. D.: On the Occurrence of a Large Area of Nepheline Syenite in the Township of Dungannon, Ontario. *Am. Jour. Sci.*, 3d ser., vol. 48, pp. 10–16, 1894.

[2] PRATT, J. H.: The Occurrence and Distribution of Corundum in the United States. U. S. Geol. Survey *Bull.* 180, p. 12, 1901.

[3] Abrasive quartz and feldspar not included.

[4] KATZ, F. J.: U. S. Geol. Survey *Mineral Resources*, 1915, part 2, p. 66, 1916.

[5] Includes volcanic ash.

much air space it is an excellent nonconductor of heat. Generally some clay or fine sand occurs in the deposits, but the pure material is nearly pure silica. It is white, cream-colored, or light gray and is easily recognized under the microscope by the symmetrical boundaries of the constituent tests. Enormous deposits are found at Reno and Goldfield, Nev., in Santa Barbara County, California, and in Oregon. Deposits are known also at Richmond, Va., and in Herkimer County, New York, Diatomaceous earth is used for packing steam pipes, for polishing powder, as an absorbent for nitroglycerine, and for many other purposes. Its great abundance and various uses promise an increasing yield.[1] In 1915 the United States produced infusorial earth valued at $611,012.

QUARTZ

Quartz is a persistent mineral, occurring in igneous and sedimentary rocks, in ore veins, in pegmatites, and elsewhere. In the West there are many big white barren mineral veins termed "bull quartz" by prospectors. Vein quartz is mined for many purposes. The purer quartzites and also flint and chert are mined in some places. Flint nodules are in demand, especially for tube mills.

Quartz is used[2] for flux, for filling acid towers, and as a refractory material. Various forms of silica are used for paint, for wood filler, for glazing, for making glass, and for mixing with clay to decrease shrinkage of pottery. As an abrasive it is used to make sandpaper, soap, and polishing powder and for the air blast. Rose quartz and some other varieties of silica are used for gems. The United States in 1915 produced 112,575 tons of silica (quartz), valued at $273,553.

GLASS SAND

By the weathering of rocks quartz is separated and accumulates along rivers, lakes, and seas. Where the sea bottoms are elevated, or where wind blows sand in dunes, the sands become more

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[1] Phalen, W. C.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 851–853, 1912.

[2] Bastin, E. S.: Quartz and Feldspar. U. S. Geol. Survey *Mineral Resources*, 1907, part 2, pp. 843–872, 1908; *Idem*, 1910, part 2, pp. 963–975, 1911.

Middleton, Jefferson: *Idem*, 1911, part 2, pp. 1027–1030, 1912.

readily available. The washing by water and blowing about by winds are generally processes of purification, and some sands are nearly pure quartz, with about 99 per cent. silica and only 1 per cent. or less total alumina, lime, magnesium, and iron. Such pure sands are used for making glass. Sandstones and pure quartzites are likewise used. If more than one per cent. of iron is present it may give the glass an undesirable color; magnesium renders the melt more difficultly fusible. Commonly some of the impurities are removed from sand by washing. Glass sands are widely distributed both geologically and geographically.[1]

GEMS AND PRECIOUS STONES

Gems are minerals used for ornaments. To be valuable, they should be rare and hard enough to be durable; they should also appeal to the taste for the beautiful. Diamond, emerald, ruby, and sapphire are the more valuable precious stones. The less valuable or "semiprecious" stones include garnet, amethyst, topaz, tourmaline, spodumene, beryl, peridot, turquoise, agate, quartz, chrysocolla—in fact, crystallized specimens of any of the harder minerals may be used for ornaments.[2] The gems and precious stones produced in the United States in 1915 were valued at $170,431.

Diamond is crystallized carbon. Its largest use is as a gem, but its hardness is 10 on the Mohs scale and considerable quantities are used as an abrasive, particularly as diamond dust and for bits of core drills. For core drills the black diamond, carbonado, is in great demand. It has no prominent cleavage and is therefore more durable. Black diamonds sell for $50 to $100 a carat. Impure white diamonds used for core drills are much cheaper. They sell at $10 a carat or more, the price

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[1] Burchard, E. F.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, p. 593, 1912.—Glass Sand of the Middle Mississippi Basin. U. S. Geol. Survey *Bull.* 285, pp. 459–472, 1906. Glass-Sand Industry of Indiana, Kentucky, and Ohio. U. S. Geol. Survey *Bull.* 315, pp. 361–376, 1907. Notes on Various Glass Sands, Mainly Undeveloped. *Idem*, pp. 377–382.

Stose, G. W.: The Glass-Sand Industry in Eastern West Virginia. U. S. Geol. Survey *Bull.* 285, pp. 473–475, 1906.

[2] For data relating to the gems produced in the United States see Kunz, G. F.: Gems and Precious Stones of North America, 1892, and several papers by D. B. Sterrett in U. S. Geol. Survey *Mineral Resources*, especially the volumes for 1909, part 2, pp. 739–808, 1910, and for 1911, part 2, pp. 1037–1078, 1912.

depending on grade and durability. Uncut gems are valued at $7 to $12 a carat or more, according to size, color, and appearance. White diamonds are most common. Those with blue tints are highly prized. Yellow diamonds are generally lower priced than white ones. The United States imports diamonds from Africa and from Brazil. The domestic production is small.

Diamonds are mined from plugs of basic igneous rocks (peridotite) in the Kimberly field, Cape Colony; at the Premier mine, near Pretoria, in the Transvaal; and in Pike County, Arkansas. They are found in placers in Brazil, India, and at many other places.

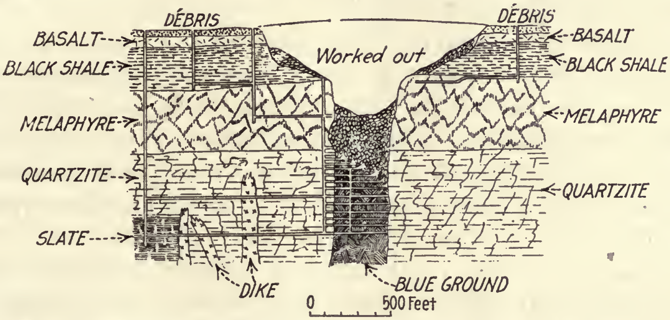

FIG. 206.—Cross-section of Kimberly peridotite plug. (*After Williams.*)

The Kimberly peridotite plug is shown in Fig. 206. The diameter decreases in depth and has been followed downward over 2,000 feet. The peridotite ("kimberlite") is extensively serpentinized. At the surface it is "yellow;" in depth, "blue ground." It disintegrates after it has been mined and exposed to the elements for a few months. The material is passed over greased tables to which the diamonds adhere. About 1 carat to the ton is recovered. The peridotite plug is intruded into a series of beds among which are carbonaceous shales. Dunn regarded the carbon of the shales as the source of the diamonds, which, according to his view, were formed by the recrystallization of carbon from the shales dissolved by the intruding magma.[1] More recent work has shown that the diamonds are original rock-making minerals. Many of the crystals are broken,[2] showing that they had formed (as phenocrysts) before the magma came to rest.

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[1] DUNN, E. J.: Notes of the Diamond Fields of South Africa. London Geol. Soc. *Quart. Jour.*, vol. 37, pp. 609–612, 1881.

[2] WILLIAMS, G. F.: "Diamond Mines of South Africa," pp. 490, 510, New York, 1902.

The deposit at the Premier mine, Transvaal,[1] is a pipe of serpentinized peridotite intruding sedimentary rocks. In Pike County, Arkansas,[2] diamonds have been formed in several small peridotite bodies that break through the Trinity (Lower Cretaceous) formation, which consists of clay, sand, gravel, and limestone. The production of Arkansas diamonds to the end of 1913 was 550 carats. The diamonds of Minas Geraes, Brazil, are obtained from placers. They are associated with fragments of quartzites and schists. Their original source is uncertain.[3]

A discussion with bibliography on occurrences and syntheses of diamonds is given by Clarke.[4]

Emerald ($Be_3Al_2(SiO_3)_6$) is a clear green variety of beryl, highly prized as a gem. It is obtained from pegmatite veins[5] and from placers. Some emeralds equal or exceed diamonds in value. Emeralds are imported from India, Ceylon, Siberia, and Brazil. In the United States they are found in pegmatites at several places in New England and in North Carolina. Beryls of colors other than green are also used for gems.

Corundum Ruby (red), sapphire (blue), oriental emerald (green), oriental topaz (yellow), and oriental amethyst (purple) are all varieties of gem corundum (Al_2O_3). The colors are probably due to small amounts of various metallic oxides. All are found in placers, where they have probably formed from the waste of igneous rocks and pegmatite dikes. Most of these varieties come from the Orient or from South America. Beautiful blue sapphires are mined from a decomposed dike of

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[1] Penrose, R. A. F., Jr.: The Premier Diamond Mine, Transvaal, South Africa. *Econ. Geol.*, vol. 2, pp. 275, 1907.

[2] Kunz, G. F., and Washington, H. S.: Diamonds in Arkansas. Am. Inst. Min. Eng. *Trans.*, vol. 39, pp. 169–176, 1908.

Miser, H. D.: New Areas of Diamond-Bearing Peridotite in Arkansas. U. S. Geol. Survey *Bull.* 540, p. 534, 1914.

[3] Derby, O. A.: Brazilian Evidences on the Origin of the Diamond. *Jour. Geol.*, vol. 6, pp. 121–146, 1898.

Branner, J. C.: The Minerals Associated with Diamonds and Carbonates in the State of Bahia, Brazil. *Am. Jour. Sci.*, 4th ser., vol. 31, pp. 480–490, 1911.

[4] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, pp. 322–328, 1916.

[5] Sterrett, D. B.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 1051–1058, 1912.

lamprophyre at Yogo Gulch, Fergus County, Montana.[1] In this dike the sapphire is a rock-making mineral. Near Philipsburg, Mont., sapphires are extensively mined from placers. In the original state they are apparently phenocrysts in a surface lava.[2] Though some of the material is of gem quality, most of it is used for watch jewels and other bearings.

Spinel ($MgO.Al_2O_3$) when red is called "spinel ruby." There are also other shades. Spinel is found in peridotite and in placers which are in part derived from basic rocks. Its hardness is 8.

Tourmaline is a complex hydrous borosilicate which may contain also magnesium and iron. It has a great variety of colors. The dark brown and black tourmalines, which contain iron, are little used as gem material. Gem tourmalines are green, white, red, yellow, etc. Gems are found at Paris, Maine,[3] and at a few other places in New England, and pink tourmaline is obtained from San Diego County, California. Gem tourmalines are found in pegmatite dikes, where they commonly occur as well-defined prismatic crystals lining small cavities. The hardness of tourmaline ranges from 7 to 7.5.

Kunzite (lilac-colored spodumene) occurs with rubellite in pegmatites in southern California. It is a gem of great beauty but is not yet widely used.

Turquoise (hydrated copper-aluminum phosphate; hardness 6) forms small veinlets in rhyolite, granite, and other igneous rocks. It is generally associated with kaolin and other secondary minerals and is probably a product of surface decomposition. It commonly fills small fractures in kaolinized igneous rock. Turquoise is obtained in several localities in Arizona[4] and other States in the arid Southwest.

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[1] Weed, W. H.: Geology of the Little Belt Mountains, Montana. U. S. Geol. Survey *Twentieth Ann. Rept.*, part 3, pp. 454–460, 1900.

Pirsson, L. V.: On the Corundum-Bearing Rocks from Yogo Gulch, Montana. *Am. Jour. Sci.*, 4th ser., vol. 4, 1897, p. 421.

Sterrett, D. B.: U. S. Geol. Survey *Mineral Resources*, 1907, part 2, p. 291, 1908.

[2] I have had an opportunity to study this material through the courtesy of Mr. O. J. Berry, of Philipsburg.—W. H. E.

[3] Bastin, E. S.: Geology of the Pegmatites and Associated Rocks of Maine. U. S. Geol. Survey *Bull.* 445, pp. 79–93, 1911.

[4] Paige, Sidney: The Origin of Turquoise in the Burro Mountains, New Mexico. *Econ. Geol.*, vol. 7, pp. 382–392, 1912.

Variscite ($AlPO_4 + 2H_2O$) is a green mineral found at a few places in Utah[1] and Nevada. A mixture of variscite matrix with chalcedony and other minerals is called "amatrice." Variscite is probably formed by processes of superficial alteration.

Peridot, a clear yellow or greenish-yellow olivine, is found in the Apache and Navajo reservations, Arizona.[2] It is associated with basic igneous rocks, from which it has separated by weathering.

Garnets (pyrope, almandine, and spessartite), are prized as gems. India is the principal source. The red garnet rhodolite of Macon County, North Carolina, is a stone of remarkable beauty. Many red garnets of fine color but of rather small size are found in the Navajo Indian Reservation, Arizona.

GRAPHITE

Graphite occurs in veins, in pegmatites, in igneous rocks, and in metamorphosed rocks. The most productive deposits in the United States are in the region of Crown Point and Ticonderoga, N. Y.,[3] where there are quartz-graphite schists that contain from 3 to 10 per cent. of graphite. The principal deposits, according to Bastin, are metamorphosed sedimentary rocks that contained organic matter. Minerals associated with the graphite include mica, feldspar, pyrite, and zoisite.

Near La Colorada, Sonora, Mexico,[4] Triassic sandstones inclosing coal beds have been metamorphosed by intruding granite and the coal beds are changed to graphite. One bed 10 feet or more thick supplies high-grade amorphous graphite that is greatly prized for making lead pencils. Graphite deposits are found also in Wisconsin, in the "Upper Peninsula" of Michigan, in the southern Appalachian region, and at many other places.

The most productive graphite deposits of the world are those

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[1] Pepperberg, L. J.: Variscite near Lucin, Utah. *Min. and Sci. Press*, Aug. 11, 1911, p. 233.

[2] Sterrett, D. B.: U. S. Geol. Survey *Mineral Resources*, 1908, part 2, pp. 832–835, 1909.

[3] Bastin, E. S.: Origin of Certain Adirondack Graphite Deposits. *Econ. Geol.*, vol. 5, pp. 134–157, 1910.—Graphite. U. S. Geol. Survey *Mineral Resources*, 1908, part 2, pp. 717–738, 1909 (contains bibliography).

[4] Hess, F. L.: Graphite Mining near La Colorada, Sonora, Mexico. *Eng. Mag.*, vol. 38, p. 36, 1909.

Bastin, E. S.: U. S. Geol. Survey *Mineral Resources*, 1908, part 2, p. 734, 1909.

of Ceylon,[1] where the graphite occurs in small veins in gneisses that are intruded by granite and pegmatite. Associated minerals are quartz, feldspar, mica, garnet, and pyroxene. There are many other occurrences of graphite associated with intruding rocks.

Graphite is used for making paints, crucibles, lubricants, lead pencils, polishing powder, etc. Amorphous graphite is preferred for lead pencils, and crystalline graphite for crucibles. Some of the graphitic rock mined carries only a small percentage of graphite and is concentrated mechanically. Material carrying as low as 30 per cent. graphite is ground and used for paint. Graphite is used also as an adulterant for fertilizer, to which it gives the black color which is popularly associated with fertility of soil. As it is insoluble, it can not add to fertility, and its use as fertilizer is to be discouraged. The United States produced in 1915 about 4,718 short tons of graphite, valued at $429,631. Most of the importations came from Ceylon and from Sonora, Mexico. A large amount of graphite is manufactured from coal at Niagara Falls.

A bibliography of graphite with brief abstracts of the more important papers is given by Bastin.[2]

BARITE

Barite ($BaSO_4$) is a common gangue mineral in ore veins, especially in those formed at intermediate and shallow depths. In deposits of the deep zone, in contact-metamorphic deposits, and in pegmatites barite is rarely present. Igneous rocks commonly contain the barium silicate molecule in feldspars. The sulphate is present in appreciable amounts in many limestones. Barite is almost insoluble, and in the weathering of limestone it collects with clay and iron oxide in the mantle rock. Nearly all the barite produced in the United States is associated with weathered limestones. It could doubtless be recovered profitably from many lode deposits of the West if markets or transportation facilities were more favorable.

The production of barite in the United States in 1915 was

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[1] Bastin, E. S.: The Graphite Deposits of Ceylon, a Review of Present Knowledge, with a Description of a Similar Graphite Deposit near Dillon, Mont. *Econ. Geol.*, vol. 7, pp. 419–443, 1912.

[2] Bastin, E. S.: U. S. Geol. Survey *Mineral Resources*, 1912, part 2, pp. 1061–1069, 1913.

108,547 short tons, valued at $381,032. The price, less than $4 a ton, is for the natural or hand-picked material at points of production. Ground and refined barite is worth about $13 a ton or more.[1]

Barite is used for making paints, especially in the manufacture of lithopone, a white paint consisting of barium sulphate and zinc sulphide made by a complex process involving the reduction of barite at high temperature. Barite is used also for treating rubber, for filling paper, and for tanning. Its great weight makes it desirable from the packer's view-point for painting ham sacks and cheese.

The most productive barite deposits in the United States are in Washington County, Missouri, in the region of the disseminated lead deposits (page 491). There Ordovician limestone is capped by residual clay. In the lower part of the clay are numerous fragments of barite, limestone and chert. Small veins and disseminated deposits of barite are found in the limestone.[2] The region has suffered great erosion, and the relations indicate that the clay and barite are residual.

In Virginia barite deposits are found as irregular pockets replacing pre-Cambrian limestone and as fissure fillings in schists, Paleozoic limestones, and Triassic limestones and shales. The deposits are concentrated by weathering and some lie in residual clay with iron oxide.[3] Small barite veins are found also in many other Eastern States.

CELESTITE

Celestite ($SrSO_4$) is found in crevices in limestones and in beds of chemical sediments, where it is generally associated with gypsum and sulphur. Rarely it is a gangue mineral of metalliferous ores. In Texas it is found in cavities of Cretaceous limestone.

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[1] Phalen, W. C.: U. S. Geol. Survey *Mineral Resources*, part 2, pp. 965–970, 1912 (contains bibliography).

[2] Buckley, E. R.: Geology of the Disseminated Lead Deposits of St. Francois and Washington Counties, Mo. Bur. Geol. and Mines, vol. 9, part 1, pp. 238–248, 1909.

Steel, A. A.: Geology, Mining, and Preparation of Barite. Am. Inst. Min. Eng. *Trans.*, vol. 40, pp. 711–743, 1910.

[3] Watson, T. L.: Geology of Virginia Barite Deposits. Am. Inst. Min. Eng. *Trans.*, vol. 38, pp. 710–733, 1907.

A noteworthy occurrence is in the Avawatz Mountains, San Bernardino County, California,[1] where celestite beds associated with salt and gypsum are included in a series of steeply tilted sediments. Locally the celestite zone is 75 feet thick. It lies below a salt bed. Celestite associated with gypsum is found about 15 miles north of Gila Bend, Ariz.,[2] in a series of tilted sedimentary beds and lava flows.

Celestite is used for making salts that are used in refining beet sugar, for making fireworks, and in medicines. The production is small.[3]

WITHERITE

Witherite ($BaCO_3$) occurs in veins and is found as a gangue mineral of a few metalliferous veins. It is abundant at Fallowfield, near Hexham, Northumberland, England, where it occurs with barite in fissures that cut Carboniferous rocks. It is found in the Rabbit Mountains, near Thunder Bay, Lake Superior. Barium salts are used for making glass, for making fireworks, and in the refining of beet sugar. They are not mined in the United States.

FLUORITE AND CRYOLITE

Fluorite, or fluorspar (CaF_2), is a common mineral in vein deposits.[4] It is found in many districts as a gangue mineral of gold, silver, and zinc veins, but in these deposits in the United States it is not exploited. The chief source of fluorite is southern Illinois,[5] where lower Carboniferous beds are extensively faulted and intruded by lamprophyre dikes. The veins dip steeply and cut across beds of limestone. Some of them are nearly 40 feet wide; some solid masses are 10 feet thick. Some galena, sphalerite, pyrite, and chalcopyrite are associated with the fluorite. The gangue minerals are quartz and calcite, and in

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[1] Phalen, W. C.: Celestite Deposits in California and Arizona. U. S. Geol. Survey *Bull.* 540, pp. 521–533, 1912.

[2] Phalen, W. C.: *Op. cit.*, p. 351.

[3] Pratt, J. H.: Strontium Ores. U. S. Geol. Survey *Mineral Resources*, 1901, part 2, pp. 955–958, 1902.

[4] Burchard, E. F.: Fluorspar and Cryolite. U. S. Geol. Survey *Mineral Resources*, 1907, part 2, pp. 607–620, 1908 (gives bibliography).

[5] Bain, H. F.: Fluorite Deposits of Southern Illinois. U. S. Geol. Survey *Bull.* 255, 1905.

some of the veins barite is present. The fluorite does not dissolve very readily from the outcrops and at some places is recovered by placer mining. At the Riley mine, Crittenden County, Kentucky,[1] fluorite ore fills a fault fissure between Carboniferous limestone and quartzite. Fluorite is found also in Boulder County[2] and at Wagon Wheel Gap,[3] Colorado; at the latter place it occurs along a fissure from which hot springs now issue.

The principal use of fluorite is for flux. About 80 per cent. of the American output, according to Burchard, is used in the steel trade in the manufacture of open-hearth steel. Fluorite is used also in making aluminum, in the electrolytic refining of antimony and lead, and for manufacturing glass, enamel, and hydrofluoric acid. The production of fluorite in the United States in 1915 was 136,941 tons, valued at $764,475. It is in good demand.

Cryolite (Na_3AlF_6) is a comparatively rare mineral. The principal deposits are at Ivigtut, in southern Greenland, where a wide vein in granite[4] carries, with much cryolite, a little siderite, quartz, pyrite, chalcopyrite, and sphalerite. Peripheral portions of the vein carry also feldspar, cassiterite, fluorite, and other minerals. A cryolite-quartz vein in granite occurs south of Pikes Peak, Colorado.[5] Cryolite imported from Greenland is used in making sodium salts, aluminum, glass, and enamel ware.

MINERAL PAINTS

Many mineral substances are used for pigments. The cheaper grades are generally fine clayey material highly colored with iron, manganese, or other minerals. In general they are residual products of the weathering of rocks containing these metals. Some earthy iron ore containing manganese is liver brown before and reddish brown after burning. Such material before burning is called "umber," and after burning "burnt umber." Sienna is

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[1] Fohs, Julius: Fluorspar Deposits of Kentucky. Ky. Geol. Survey *Bull.* 9, 1907.

Miller, A. M.: The Lead and Zinc-Bearing Rocks of Central Kentucky. Ky. Geol. Survey *Bull.* 2, p. 25, 1905.

[2] Burchard, E. F.: *Op. cit.*, pp. 612–617.

[3] Emmons, W. H., and Larsen, E. S.: The Hot Springs and Mineral Deposits of Wagon Wheel Gap, Colorado. *Econ. Geol.*, vol. 8, p. 242, 1913.

[4] Quale, Paul: An Account of the Cryolite of Greenland. Smithsonian Inst. *Rept.*, 1866, p. 398.

[5] Dana, J. D.: "System of Mineralogy," 6th ed., p. 167, 1892.

a similar material, but of lighter color, probably due to hydrated iron oxide, limonite.

Ocher is the yellow iron oxide, limonite, incorporated in a clay base. Cinder from acid making (iron oxide), roasted siderite, and raw hematite are ground and used to make red paint. Black clay, shale, and slate are ground and used as fillers and as pigments. Some slates are distilled and both the residue and the oil recovered are used in making paint. Calcium carbonate—limestone, calcite, and shells—is ground and used as "whiting." Slaked lime is used extensively for whitewash. Iron oxide, ground shales, and culm from coal washeries are used for mortar colors. Graphite, gypsum, asbestos, barite, asphalt, and magnesite, discussed elsewhere, are all used as pigments. High-grade paints are made from compounds of lead, zinc, mercury, cobalt, arsenic, etc. The United States produced 57,442 short tons of natural pigments in 1915, valued at $551,598. More detailed information is given in reports of the United States Geological Survey.[1]

SALT

General Occurrence.—When sea water is evaporated, its mineral salts are precipitated—the least soluble first. The order of precipitation depends not only on the solubility of the salts in pure water, but also upon concentration, temperature, pressure, and other salts dissolved in the water. If certain minor constituents such as iron, manganese, and phosphorus are omitted the composition of the ocean may be stated as follows:[2]

Composition of oceanic salts	
$NaCl$	77.76
$MgCl_2$	10.88
$MgSO_4$	4.74
$CaSO_4$	3.60
K_2SO_4	2.46
$MgBr_2$	0.22
$CaCO_3$	0.34
	100.00

Composition of ocean	
O	85.79
H	10.67
Cl	2.07
Na	1.14
Mg	0.14
Ca	0.05
K	0.04
S	0.09
Br	0.008
C	0.002
	100.000

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[1] See particularly PHALEN, W. C.: Mineral Paints. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 970–993, 1912 (contains an extensive bibliography).

[2] CLARKE, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 23, 1916.

If sea water is evaporated to dryness, the salts will separate approximately in the following order: Calcium carbonate with a little iron oxide, calcium sulphate, sodium chloride, magnesium sulphate and magnesium chloride, sodium bromide, and potassium chloride and sulphate. At some stages,[1] two or more of the salts are precipitated simultaneously. If an arm of the sea is shut off from the main body, its water evaporated, and the resulting salts covered by clay or some other impermeable bed, the saline deposit will be preserved. Such is probably the origin of the famous deposits of Stassfurt, Germany.[2] There the beds from the bottom up are (1) anhydrite and gypsum, (2) rock salt and anhydrite, (3) polyhalite (hydrated lime-magnesium, potassium-sulphate), (4) kieserite ($MgSO_4.H_2O$), (5) carnallite ($KMgCl_3.6H_2O$), locally overlain by sylvite (KCl). Above the potash salts is a bed of clay, and above that more anhydrite and salt, indicating probably a later precipitation from the sea water. The salt deposits are covered by thick beds of sandstone and are worked through deep shafts. They were first worked for salt but have more recently furnished the world's chief supply of potash minerals that are extensively used for fertilizer.

Origin of Thick Salt Beds.—Some salt beds are 1,000 feet or more thick. The volume of the salts precipitated from sea water is less than 2 per cent. of the water. For 1,000 feet of salt to be deposited by precipitation over the floor of a basin it is necessary to assume a volume of salt water having the concentration of the ocean equal to a depth of 50,000 feet over the basin. So deep a basin appears improbable. Even if we assume a shrinking lake or inland sea, which would of course result in concentrating the salts over a smaller area, the hypothesis still appears improbable, for the basin required would be much deeper than any existing today.

To account for the great thicknesses of some salt beds, Ochsenius proposed the "bar" hypothesis, in which it is supposed that sea water passes over a bar into a large basin near shore, and that evaporation is balanced by a flow of water from the sea over the bar. When evaporation reaches a certain stage precipitation begins. Concentration may go only far enough

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[1] Usiglio, J.: *Annales chim. phys.*, 3d ser., vol. 27, pp. 92, 172, 1849.

[2] For a clear discussion of this subject with numerous references see Clarke, F. W.: *Op. cit.*, pp. 221–228.

to precipitate gypsum or only far enough to precipitate gypsum and salt, and the more soluble salts may be carried by reversed movement of water back to the sea. If a bar finally rises and shuts in the bittern or magnesium and potassium solutions from which salt and gypsum have been precipitated, then the sulphates and chlorides of magnesium and potassium will be precipitated above the sodium chloride. This hypothesis of course demands a nice adjustment of conditions, which is probably rarely met; it is noteworthy, however, that the potash salts are not associated with all deposits of salt and gypsum. In fact, thus far they have not been developed in great abundance except in the Stassfurt region.

Salt Deposits of the United States.—In the United States salt is obtained from beds of Paleozoic and later age and from basins where evaporation is now going on. At most places it is obtained by the evaporation of brines pumped from the saline rocks. The production of salt in 1915 was 38,231,496 barrels, valued at $11,747,686. In New York salt is obtained by pumping brines from the Salina (Silurian) beds, where, with gypsum, it occurs as lenses in shales.[1]

In Michigan brines are obtained from Mississippian sandstones in Saginaw Valley. Water is pumped into the sands and pumped out with dissolved salt. The brines from the upper beds of the Marshall formation, are rich in bromine and supply most of the bromine output of the United States. Much of the salt is utilized in manufacturing sodium carbonate.[2]

In Ohio[3] salt is obtained from brines from the Mississippian and also from the Salina beds. In Kansas salt is mined from Permian rocks by means of shafts and obtained from salt springs. In the Western States salt is obtained from undrained basins where it is forming today. At Saline Valley, Inyo County, California,[4] a deposit of salt occupies about a square mile in a deep basin. This pure-white salt (98.52 per cent. NaCl) requires no refining. In the center of the deposit there is a small pool of salt water.

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[1] MERRILL, F. J. H.: N. Y. State Mus. *Bull.* 11, 1893.

[2] COOK, C. W.: The Brine and Salt Deposits of Michigan. Mich. Geol. and Biol. Survey, Geol. ser. 12, pp. 1–188, 1914.

[3] BOWNOCKER, J. A.: Salt Deposits and the Salt Industry in Ohio. Ohio Geol. Survey, 4th ser., vol. 8, pp. 1–42, 1906.

[4] GALE, H. S.: Salt, Borax and Potash in Saline Valley, Inyo County, California. U. S. Geol. Survey *Bull.* 540, pp. 416–422, 1914.

On the Gulf coast in Louisiana and Texas there are some of the most remarkable salt deposits in the world. Shafts and bore holes sunk in low knobs or domes, some of which project as low islands above marshes, encounter bodies of salt 2,000 feet thick or more. The associated rocks are Tertiary and Quaternary sands, limestones, and clays. The beds have quaquaversal dips away from the salt deposits, which structurally resemble laccolithic intrusions. Some have thought that the salt deposits were formed by precipitation along fissures by ascending hot solutions, and Harris[1] believes that the force of crystallization has bowed up the rocks into the characteristic domes. That such a force should be so potent seems incredible, yet the "bar" hypothesis seems inadequate to account for these unusual deposits.

Limestone beds are found above the salt beds in several of the domes. At Spindletop, Texas,[2] and in some other salt domes of the coast region petroleum is associated with the salt, and sulphur also is found in some of the deposits. It has been suggested that the salt, gypsum, and petroleum have been formed together, and that the petroleum has reduced the calcium sulphate, forming free sulphur from it.

As Lindgren[3] has noted, the plasticity of salt is great. It would be difficult to imagine a less "competent" bed than rock salt soaked with water. Pressure on the rocks that formed the anticlinal folds and domes may possibly have caused also a marked thickening of the salt beds at crests of anticlines. Thin limestones inclosed in sandy rocks, when subjected to folding, are generally thickened at anticlines. Wet salt, which is much more yielding than calcite, may respond to this process under stresses that are relatively slight and where the rocks are under comparatively light load. In the Stassfurt field, where the salt series is obviously folded, there is a notable thickening of the salt bed at the Engeln anticline.

One other remarkable feature of these domes and "islands" should be mentioned. In some areas several of them are in

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[1] HARRIS, G. D.: Rock Salt: Its Origin, Geology, and Occurrence. La. Geol. Survey *Bull.* 7, 1908.

[2] FENNEMAN, N. M.: Oil Fields of the Texas-Louisiana Gulf Coastal Plain. U. S. Geol. Survey *Bull.* 282, pp. 119–121, 1906.

HAHN, F. F.: The Form of Salt Deposits. *Econ. Geol.*, vol. 7, pp. 120–135, 1912.

[3] LINDGREN, WALDEMAR: "Mineral Deposits," p. 289, New York, 1913.

alignment, as at Vermilion Bay, La. The Avery salt dome, on Petite Anse Island, is in line with four others.[1] To one inclined to regard these deposits as having been formed by precipitation from ascending waters this alignment would suggest the presence of a great fissure. Such an alignment might result, also, by the development of small domes along an anticline.[2] The origin of these deposits must be regarded as still in doubt. The hypothesis that attributes their deposition to ascending hot waters is not entirely satisfactory, because in thousands of ore veins formed by ascending hot waters the presence of salt is practically unknown, except in small fluid inclusions that are locally developed in the wall rocks. The sedimentary origin of salt deposits is indicated by the fact that essentially all of them occur in sedimentary rocks. Igneous and metamorphic rocks are barren of salt deposits.

POTASH SALTS

Potash salts[3] are important economically because they are necessary for plant life. Potash is one of the abundant constituents of the earth's crust; several per cent. of it is present in granites, pegmatites, and leucite rocks, in which, however, it is relatively insoluble and not readily available. Potash constitutes a considerable percentage of alunite, a mineral that is abundant at Goldfield, Nev., at Marysvale, Utah, and at several other places in the West. By calcination alunite is dehydrated and loses some SO_3, and its potassium sulphate is rendered soluble. Small amounts of potash are obtained by leaching wood ashes, and it has been recovered also from sea weeds, some of which contain potash in notable quantities.

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[1] This is shown by Hilgard's map reproduced in MERRILL, G. P.: "Nonmetallic Minerals," p. 51, New York, 1910. The original is not accessible to me.

[2] HAYES, C. W., and KENNEDY, WILLIAM: Oil Fields of the Texas-Louisiana Gulf Coastal Plain. U. S. Geol. Survey *Bull.* 212, pp. 143–144, 1903.

[3] SCHULTZ, A. R., and CROSS, WHITMAN: The Potash-Bearing Rocks of the Leucite Hills, Wyoming. U. S. Geol. Survey *Bull.* 512, 1912.

BUTLER, B. S., and GALE, H. S.: Alunite. U. S. Geol. Survey *Bull.* 511, 1912.

ZIEGLER, VICTOR: The Potash Deposits of the Sand Hills Region of Northwestern Nebraska. Colo. School of Mines *Quart.*, vol. 10, No. 3, pp. 6–26, 1915.

Nearly all the potash used in the United States has come for many years from the Stassfurt salt beds in Germany. In recent years the United States Geological Survey has been engaged in a search for potash[1] in some form readily available for agriculture. Many lakes, marshes, and playa deposits of California and Nevada have been drilled and sampled. At Searles Marsh, in San Bernardino County, California, a thick salt bed having an area of 11 square miles is saturated with brine exceptionally rich in potash. Potash was obtained on a commercial scale from alkali lakes in Nebraska in 1916.

Some igneous rocks carry a percentage of K_2O approximately equal to that of commercial potash salts used for fertilizer. The invention of some smelting process by which the potash of silicates might cheaply be rendered soluble would prove a great service to mankind.

BROMINE

Bromine is found as bromides in sea water and in some brines. In Michigan, West Virginia, and Pennsylvania it is obtained from brine incidentally to the manufacture of salt. The lower Carboniferous salt beds are locally high in bromine.[2]

Bromine is used in chemistry, in photography, in medicine, and as a disinfectant. The United States in 1915 produced 855,857 pounds, valued at $856,307.

SODIUM SULPHATE

Sodium sulphate ($Na_2SO_4.10H_2O$) is deposited in abundance in some inland basins where mineral waters are evaporated. Much of this material is obtained as a by-product in manufacturing hydrochloric acid and other salts, and the natural product sells at a low price. Sodium sulphate is precipitated from water relatively low in calcium and magnesium before sodium chloride is formed. Its solubility is appreciably affected by slight changes in temperature. At Great Salt Lake, Utah, it is precipitated

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[1] GALE, H. S.: The Search for Potash in the Desert Basin Region. U. S. Geol. Survey *Bull.* 530, pp. 295–312, 1913.

YOUNG, G. J.: Potash Salts and Other Salines in the Great Basin Region. U. S. Dept. Agr. *Bull.* 61, pp. 1–96, 1914.

[2] LANE, A. C.: "Mineral Industry," vol. 16, p. 123, 1907. See also volumes of U. S. Geol. Survey *Mineral Resources,* especially an article by F. J. H. MERRILL in volume for 1904, pp. 1029–1030, 1905.

during the winter and cast up on the shore. In summer it is redissolved. Formerly the harvesters in winter removed the salt from the reach of the waves and collected it at leisure.[1]

Near Laramie, Wyo., sodium sulphate has been gathered from small lakes that dry up in the summer. Deposits are known at many places in the arid West. Sodium sulphate is used in the manufacture of paper and glass and for medicine.

GYPSUM

Gypsum ($CaSO_4.2H_2O$) occurs in beds and is commonly associated with salt. Sea water contains a considerable proportion of calcium sulphate, which on evaporation is deposited before sodium chloride. Although gypsum is commonly formed by the superficial alteration of sulphide ores, the principal gypsum deposits are of sedimentary origin. Many of them are associated with "Red Beds" and have been formed by the evaporation of sea water under arid conditions in inclosed basins or in arms of the sea.

Anhydrite ($CaSO_4$) is likewise precipitated from sea water. It is not so desirable as gypsum for most purposes. By long exposure anhydrite becomes hydrated, forming gypsum, and some of the workable gypsum beds have been formed in this way.

Extensive gypsum beds occur in many States of the Union. They are widely distributed in Paleozoic and Mesozoic rocks and are found also in the Tertiary. In New York gypsum is interbedded with shales and shaly limestones in the Salina formation. The beds worked are from 4 to 30 feet thick. Some of the deposits are worked underground, and some are quarried. The gypsum-bearing area, which is 150 miles long, lies a few miles south of and parallel to the south shore of Lake Ontario.[2]

In northern Ohio gypsum is found in the Monroe formation (Silurian). In Michigan[3] gypsum is mined from deposits interstratified with lower Carboniferous shale and limestone.

In Iowa, near Fort Dodge,[4] gypsum, probably of Permian

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[1] Talmage, J. E.: *Science*, new ser., vol. 14, p. 446, 1889.

[2] Newland, D. H., and Leighton, Henry: Gypsum Deposits of New York. N. Y. State Mus. *Bull.* 143, 1910.

[3] Grimsley, G. P.: The Gypsum of Michigan and the Plaster Industry. Mich. Geol. Survey, vol. 9, part 2, 1904.

[4] Wilder, F. A.: Geology of Webster County. Iowa Geol. Survey *Ann. Rept.*, vol. 12, pp. 65–235, 1901.

age, is mined. Locally it rests on the "Coal Measures" and is covered with glacial drift. The gypsum bed is from 10 to 25 feet thick.

In southwestern Virginia[1] gypsum associated with salt and anhydrite is found in Carboniferous gray and red clays. The rocks dip 25° to 45°, and some beds are 30 feet thick.

In Kansas[2] gypsum deposits are mined in a belt that extends northeastward across the State. The beds are associated with Permian red shales. Some of the Kansas deposits have been formed by solutions that dissolved rock gypsum from the beds and precipitated the calcium sulphate as gypsite or earthy gypsum in swamps and marshes near by. The material is used for making wall plaster.

Large gypsum deposits are found in western Oklahoma and around the Black Hills, South Dakota.

In New Mexico[3] a gypsum bed 60 feet thick is associated with limestone, red shale, and pink sandstone in the "Red Beds."

Gypsum is used in the manufacture of wall plaster, land plaster, stucco, plaster of Paris, and various cements. The ground powder, unburned, is used to retard the set of Portland cement. Land plaster is powdered gypsum, unburned, used for fertilizer. The white powder is used in making paint, crayons, and paper and for an adulterant. White massive gypsum (alabaster) is used by sculptors for making ornaments. Gypsite, an impure unconsolidated mixture of gypsum and clay, or of gypsum, clay, and sand, is used for making wall plaster, in which the clay serves as a retarder. Plaster boards, building blocks, and various other forms are made from gypsum plaster.[4]

Gypsum contains, besides combined water, a variable content of absorbed moisture. If it is heated to a temperature between 212° and 400° F., depending on the impurities it contains, the free moisture and part of the combined water are driven off:

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[1] Eckel, E. C.: Salt and Gypsum Deposits of Southwestern Virginia. U. S. Geol. Survey *Bull.* 213, pp. 406–416, 1903.

[2] Grimsley, G. P., and Bailey, E. H. S.: Special Report on Gypsum and Gypsum Cement Plasters. Kans. Univ. Geol. Survey, vol. 5, p. 82, 1899.

[3] Shaler, M. K.: Gypsum in Northwestern New Mexico. U. S. Geol. Survey *Bull.* 315, pp. 260–266, 1907.

[4] Burchard, E. F.: Gypsum. U. S. Geol. Survey *Mineral Resources,* 1910, part 2, pp. 717–733, 1911 (contains bibliography and a map showing distribution of gypsum plants in the United States).

$CaSO_4.2H_2O$ becomes $2CaSO_4.H_2O$. The partly dehydrated material is ground, and when water is added it sets again, forming more highly hydrated calcium sulphate. If it is raised to too high a temperature the gypsum becomes "dead burned" and will not readily set on addition of water.

The production of gypsum in the United States in 1915 amounted to 2,447,611 tons, valued at $6,596,893.

SULPHUR

Although sulphur is present in sulphides in most lode deposits of the metals, native sulphur forms only sparingly by oxidation of sulphide ores, and lode deposits produce little commercial sulphur. The sulphur supply is obtained from sedimentary beds that carry sulphur, from deposits formed near volcanic vents and at the orifices of hot springs that yield hydrogen sulphide, and from extinct volcanic and fumarolic centers. The sulphur has evidently been formed near the surface by the oxidation of hydrogen sulphide. In the presence of oxygen the following reaction probably takes place:

$$H_2S + O = H_2O + S.$$

The largest sulphur deposits are found in Calcasieu Parish, Louisiana. Below about 400 feet of unconsolidated sandstone is a bed of gypsum and sulphur with some organic matter. The deposits were discovered in boring for oil, and attempts were made to sink shafts to them, but that was found to be impracticable in the loose sandy beds overlying the sulphur beds. The deposits are now successfully worked by the Frasch process. Two pipes, one inside the other, are sent down to the sulphur bed, and superheated water or steam is discharged through one pipe at the bottom of the well, melting the sulphur, which rises with the hot water through the other pipe and solidifies on cooling in the air. The process also refines the sulphur, a pure product being obtained.

The deposits occupy an anticline in Cretaceous sedimentary rocks. The area has been outlined by drilling and is rudely circular and over half a mile in diameter. The sulphur bed is locally more than 100 feet thick, and much of it contains about 70 per cent. of sulphur. The sulphur is associated with limestone and gypsum and is underlain by gypsum. These deposits[1] contain large reserves.

Valuable deposits of sulphur are found also near Bryan Heights, Texas,[2] in a structural dome that has yielded oil and gas. The sulphur is associated with salt, gypsum, and limestone.

Before the development of the Frasch process and the exploitation of the Louisiana deposits Sicily was the chief source of the world's sulphur supply. The Sicilian sulphur deposits lie in tilted strata and are associated with limestone and gypsum. The sulphur in these deposits is believed by many to be of syngenetic origin,[3] although the method of their formation is not yet clearly elucidated.

The origin of sulphur beds has long been a subject of controversy. It is supposed by some that organic matter has reduced gypsum, forming calcium sulphide, which was further decomposed by carbon dioxide and oxygen, yielding calcium carbonate and sulphur. This reaction has not been verified experimentally, and the genesis of these deposits is still in doubt. A plausible hypothesis has been stated by Hunt,[4] who believes that the sulphur is formed by the destruction of gypsum through the agency of certain anaerobic bacteria that consume calcium sulphate and liberate hydrogen sulphide. Such organisms are now active in the Black Sea. The oxidation of the hydrogen sulphide would set free sulphur, as noted above.

At Sulphurdale, Utah,[5] and at Cody, Wyo.,[6] sulphur has been deposited in shattered lavas, probably by hydrogen sulphide gases. At Cody such gases now issue copiously from vents

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[1] Hayes, C. W., and Kennedy, William: Oil Fields of the Texas-Louisiana Gulf Coastal Plain. U. S. Geol. Survey *Bull.* 212, pp. 133–135, 1903.

Harris, G. D.: Oil and Gas in Louisiana. U. S. Geol. Survey *Bull.* 429, pp. 99–103, 1910.

[2] Phalen, W. C.: Sulphur, Pyrite, and Sulphuric Acid. U. S. Geol. Survey *Mineral Resources*, 1912, part 2, pp. 931–953, 1913.

[3] Stutzer, Otto: "Die wichtigsten Lagerstätten der Nicht-Erze," p. 474, Berlin, 1911. Translated by Phalen, W. C.: *Econ. Geol.*, vol. 7, pp. 732–745, 1912.

[4] Hunt, W. F.: The Origin of Sulphur Deposits in Sicily. *Econ. Geol.*, vol. 10, pp. 543–579, 1915.

[5] Lee, W. T.: The Cove Creek Sulphur Beds, Utah. U. S. Geol. Survey *Bull.* 315, pp. 485–489, 1907.

[6] Woodruff, E. G.: Sulphur Deposits at Cody, Wyo. U. S. Geol. Survey *Bull.* 340, pp. 451–456.

near sulphur deposits. At Thermopolis, Wyo.,[1] sulphur is obtained below travertine that rests on limestone.

In Hokkaido, Japan, sulphur is recovered from an old volcanic crater. Sulphur is said to occur in commercial quantites near Popocatapetl, Mexico, and other volcanoes.

A large part of the sulphur produced is utilized in the paper industry, in which it is converted into sulphite and used for bleaching paper pulp. A little sulphur is used in making sulphuric acid, but most sulphuric acid is made by burning sulphide minerals. Because sulphur ignites at a low temperature it is used in making matches, gunpowder, and fireworks. Sulphur dioxide is used extensively for bleaching. Sulphur is used for spraying vegetation to protect it against fungous diseases, as a preservative, and for vulcanizing rubber.

In 1914 the United States produced 327,634 long tons of sulphur, valued at $5,479,849. Most of this was from Louisiana; a little came from Texas, Nevada, and Wyoming.

PYRITE AND SULPHURIC ACID

Pyrite, marcasite, pyrrhotite, sphalerite, and sulphur are used for making sulphuric acid. The roasted minerals give off sulphur dioxide, which is led into a Glover tower, where nitrogen oxides and steam are introduced. Sulphur dioxide is oxidized to sulphur trioxide, with which a molecule of water unites, forming sulphuric acid. Part of the nitrogen compounds after having oxidized the sulphur dioxide are recovered in Gay-Lussac towers. Thus the process with respect to nitrogen is regenerative.

The huge acid plants in the Ducktown district, Tennessee, use blast-furnace gases obtained from smelting pyrrhotite-chalcopyrite copper ores. Some plants make acid from fumes obtained by roasting sphalerite as a preliminary to charging it in zinc retorts. Marcasite is obtained by separating the iron sulphide from zinc sulphide in zinc concentrates. The principal output of marcasite comes from the zinc ores of southwestern Wisconsin and northwestern Illinois.

Pyrite is mined in several Eastern States, and considerable pyrite is now obtained as a by-product of coal mining in Illinois, Indiana, and Ohio. At some plants the cinder obtained from

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[1] Woodruff, E. G.: Sulphur Deposits near Thermopolis, Wyo. U. S. Geol. Survey *Bull.* 380, pp. 373–380.

burning pyrite for acid making is subsequently leached for the extraction of copper and smelted for iron. Pyrite is imported from Canada and Spain. The Spanish pyrite from the Huelva or Rio Tinto region is of high grade and abundant. It is received in large quantities at eastern ports.

Virginia is an important producer of domestic pyrite. In Louisa County there are huge lenticular deposits of pyrite in garnet-mica schist which is probably a metamorphosed limestone.[1] Minerals associated with the pyrite include chalcopyrite, galena, sphalerite, pyrrhotite, magnetite, actinolite, calcite, and garnet. The lenses of pyrite ore are rudely in alignment or overlap. According to Watson they have replaced sedimentary beds. Pyritic lenses in schist are worked also in Prince William County, Virginia. In St. Lawrence County, New York,[2] near Canton and Gouverneur, deposits of low-grade pyrite in schist are mined and concentrated. At the Davis mine, Franklin County, Massachusetts, a deposit of high-grade pyrite in schist was mined for many years but is said now to be exhausted. At the Milan mine, New Hampshire,[3] a pyritic deposit in schist is mined and concentrated for pyrite. Considerable pyrite is mined in California in the foothill copper belt and in Shasta County.

In 1915 the United States produced 394,124 long tons of pyrite, valued at $1,674,933.

BORON COMPOUNDS

Boron is a comparatively rare element. It is present in the silicates, tourmaline, axinite, and datolite, but these are not important as sources of boron. Borax compounds are present also in many hot springs. In arid regions borax salts are formed by the evaporation of water in closed basins. Nearly all the boron compounds of commerce are obtained from bedding-plane deposits of borax minerals that are interlayered with sedimentary rocks. These are found principally in areas of late volcanic activity.

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[1] Watson, T. L.: "Mineral Resources of Virginia," p. 190, Lynchburg, 1907.

[2] Smyth, C. H., Jr.: On the Genesis of the Pyrite Deposits of St. Lawrence County. N. Y. State Mus. *Bull.* 158, p. 143, 1912.

[3] Emmons, W. H.: Some Ore Deposits of Maine and the Milan Mine, New Hampshire. U. S. Geol. Survey *Bull.* 432, pp. 50–60, 1910.

The water of Clear Lake, California,[1] contains an unusual proportion of boron compounds. Formerly the water was evaporated for borax salts on a commercial scale. The solid matter in a spring on the margin of this lake contains 25.61 per cent. B_4O_7.

The principal borax minerals are colemanite ($Ca_2B_6O_{11}.5H_2O$), borax ($Na_2B_4O_7.10H_2O$), ulexite ($CaNaB_5O_9.8H_2O$), and boracite ($Mg_7Cl_2B_{16}O_{30}$). Of these, colemanite supplies practically the total output of borax in the United States. A little boracite is obtained from the Stassfurt region, Germany, and some borates are recovered as by-products from the evaporation of brines. Pandermite is a lime borate near colemanite in composition, but it does not decrepitate on heating and is not used at present.

Boron minerals are found in both syngenetic and epigenetic deposits. Some have been formed probably by the evaporation of waters that have leached older bedded deposits. Some of the older deposits are doubtless the result of desiccation of hot-spring waters in ancient closed basins; others have been formed in fissures and fractured zones. The soluble borax minerals[2] are removed readily from outcrops. Some outcrops of colemanite are marked by gypsum.

The Lila C. borax mine, in Death Valley, California, is at present the principal source of borax.[3] The borax beds are associated with Tertiary shales, sandstones, and vesicular lavas. The strata are steeply tilted and faulted. The borax beds, which occur at definite stratigraphic horizons, dip about 45.° The principal borax mineral is colemanite, the beds of which are locally 15 feet or more thick.

At Stauffer, Ventura County, California, colemanite deposits occur in folded and faulted sedimentary rocks closely associated with beds of basalt that inclose zones of shale and massive limestone. The limestone beds contain the largest borate deposits

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[1] Becker, G. F.: Geology of the Quicksilver Deposits of the Pacific Slope. U. S. Geol. Survey *Mon.* 13, pp. 265, 440, 1888.

[2] Gale, H. S.: The Origin of Colemanite Deposits. U. S. Geol. Survey *Prof. Paper* 85, pp. 1–9, 1913.

[3] Gale, H. S.: The Lila C. Borax Mine at Ryan, Calif. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 861–866, 1912.

Campbell, M. R.: Reconnaissance of the Borax Deposits of Death Valley and Mohave Desert. U. S. Geol. Survey *Bull.* 200, pp. 1–23, 1902.

in the field. The limestone is sheeted, shattered, and cemented and partly replaced by colemanite.

Borax compounds are used for preservatives, in chemistry, as cleansers and insecticides, and for making glass, paints, cosmetics, etc. The United States produced in 1915 about 67,003 tons of borax, valued at $1,677,099.

NITRATES

Sodium nitrate ($NaNO_3$, Chile niter) and potassium nitrate (KNO_3, saltpeter) are readily soluble in water and therefore are found only in arid regions or in caves or other places where they are protected from rain. These salts are formed by the decomposition of organic waste through the agency of nitrifying bacteria. Nitrate deposits occur in Death Valley, California, and at other places in the United States, but these are probably of small value. The world's supply of nitrates is obtained mainly from the Atacama and Tarapaca desert region of Chile. In 1912 Chile produced 2,585,850 metric tons of sodium nitrate, valued at $107,054,090.[1]

The deposits are found here and there along the coast for a distance of about 450 miles. They are on a plateau about 2,500 feet above the sea, west of the Andes. The country is arid: rain falls at intervals of about ten years. The arid plateau is composed of Jurassic rocks covered with marine sands, gravel, clay, and mud and angular fragments from the hills. The nitrate-bearing mixture, or caliche, is associated with the unconsolidated material. As a rule, sodium chloride, alkali and alkali earth sulphates, sodium borate, and other salts are present. The impure nitrate mixtures are purified by dissolving in hot water and by fractional crystallization.

Over the origin of the Chile nitrate deposits there is much controversy. One hypothesis is that the nitrates of the caliche have been derived from the air by oxidation of nitrogen through the agency of static electricity.[2] In Europe nitrates are produced artificially by oxidation of nitrogen of the air in the electric arc. It is said, however, that electrical effects are not more pronounced in the desert regions of Chile than in other desert regions

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[1] Strauss, L. W.: The Chilean Nitrate Industry. *Min. and Sci. Press*, vol. 108, p. 972, 1914.

[2] Semper, E., and Michels: Die Saltpeterindustrie Chiles. *Zeitschr. Berg-, Hütten- u. Salinenwesen preuss. St.*, vol. 52, pp. 359–482, 1904.

where nitrates do not accumulate. The most generally accepted theory is that the nitrate mixture has been derived from the leaching of material formed by the action of nitrifying bacteria on organic matter in the soil.[1] This organic matter is supposed to be in part of animal origin. Guano deposits occur in parts of the nitrate region. Penrose[2] considers it probable that the deposits have originated through the leaching of nitrate from extensive deposits of bird guano that accumulated before the coast range was thrown up, the leachings having mingled with the salines of a closed basin. Although the country is extremely arid, the ground-water nevertheless stands near the surface, being supplied by the mountains near the border. Singewald and Miller[3] note that the nitrate deposits occur at the places where the ground water comes near the surface and where the soil is porous and believe that the accumulation of nitrates is due to abnormally rapid evaporation of great quantities of ground water under extremely arid conditions. They also believe, however, that the quantities of nitrates carried by the water are above the average, and they note the presence of skeletons of birds and guano in the desert basin.

The uses of nitrates for fertilizer and for making sulphuric acid and explosives are well known.

MINERAL FERTILIZERS

Plants subtract from soils each year appreciable amounts of mineral matter. Unless this is replenished, the productivity of the soil will ultimately be impaired. For some crops, especially for grains, lime, potash, phosphorus, and nitrates are necessary. Any one or all of these may be insufficient in the soil. Lime is supplied as limestone, marl, or gypsum. Limestone and marl are especially useful when it is desired to correct acid soils. The limestone is generally ground to fine dust and sometimes it is calcined and slaked before grinding. Gypsum is sold in the raw

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[1] Müntz, A.: Recherches sur la formation des gisements du nitrate de soude. *Compt. Rend.*, vol. 101, pp. 1265–1267, 1885.

[2] Penrose, R. A. F., Jr.: The Nitrate Deposits of Chile. *Jour. Geol.*, vol. 18, pp. 1–32, 1910.

[3] Singewald, J. T., Jr., and Miller, B. L.: The Genesis of the Chilean Nitrate Deposits. *Econ. Geol.*, vol. 11, pp. 103–114, 1916.

state finely ground. When used for fertilizer, it is called land plaster. Potash is supplied as the sulphate (kainite) and as niter (potassium nitrate), though niter is too expensive for general use. Greensand marl, which contains some potash in the mineral glauconite (a hydrous iron and potassium silicate), is also used as a fertilizer. The potash in glauconite is less readily available, however, for it dissolves but slowly. Phosphorus is supplied by bone phosphate, rock phosphate, apatite, and wavellite; all are generally treated with sulphuric acid to make the phosphate more soluble. Recently finely ground phosphate rock has been applied to soils in the raw state, but as it is slowly soluble a longer time must elapse before the investment yields returns. Mineral phosphates compete with bone meal and fish waste, which contain calcium phosphate. In Europe the phosphates obtained by the basic open-hearth process of making steel are used for fertilizer.

Nitrates are formed in soils by certain bacteria working in conjunction with leguminous plants; deficiency in nitrates, therefore, may be corrected by suitable rotation of crops. Some commercial fertilizers contain sodium or potassium nitrates or ammonia salts.

Guano, used for fertilizer, is the excrement of animals, chiefly of birds and bats. Some islands of the sea are thickly covered with a mantle of guano, and formerly large quantities of this material were imported, especially from Peru. In Texas bat guano has been recovered from caves.[1]

Sulphuric acid is extensively used to convert rock phosphate and bones into the more soluble superphosphate. Thus there is a close relation between the acid and phosphate fertilizer industries, and many fertilizer companies operate acid plants.

Phosphate rock is a noncrystalline material, principally lime phosphate; it contains as a rule 25 to 35 per cent. P_2O_5, and about 40 to 50 per cent. CaO. Other radicles commonly present are SiO_2, Al_2O_3, Fe_2O_3, and $CaCO_3$. Apatite $[(CaF)\ Ca_4(PO_4)_3]$ contains 42.3 per cent. P_2O_5. Wavellite has the formula $4AlPO_4.2Al(OH)_3 + 9H_2O$, which corresponds to 35.2 per cent. P_2O_5. Of these products phosphate rock yields much the greatest quantity of fertilizer. In 1915 the United States produced

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[1] Phillips, W. B.: Bat Guano Caves. *Mines and Minerals*, vol. 21, p. 440, 1901.

1,835,667 tons of phosphate rock, valued at $5,413,449; nearly all of this was from Florida, Tennessee, and South Carolina. A little apatite is produced as a by-product of the magnetic separation of iron ores in the Adirondack region, New York.

Phosphate rock occurs in sedimentary beds or as surface concentrations formed by the weathering of such beds. It is commonly associated with marine limestone and is generally of marine origin. Its color is white, gray, brown, blue, or black, depending on impurities. Some of it is made up of numerous shells or fragments of shells. The pisolitic or oolitic texture is very common.

Of the origin of phosphate rock there is yet much to be learned. Some is doubtless formed by the bodies and waste of marine animals. Some is probably precipitated directly from sea water. Richards and Mansfield[1] regard the oolitic texture of Idaho phosphate as original. Shells of animals that normally have lime carbonate shells are found to be made up of mixtures of lime carbonate and lime phosphate.

The textural features of some phosphate rocks are similar to those found in Alabama hematites (page 323). The beds of phosphate and hematite are likewise very extensive. Doubtless the origin of both is closely similar, and probably some phosphate is precipitated directly from sea water and other phosphate replaces calcareous material on the sea bottom. Where phosphatic limestone weathers lime carbonate is removed more rapidly than lime phosphate.

Some deposits form residual masses due to surface concentration. The western deposits (Fig. 207) are generally richer at the outcrop than in depth, owing to the removal of lime carbonate. There are many beds in the West, however, that are high grade in what appears to be the original concentration. Here also, in their enrichment these deposits show a similarity to the Clinton type of iron ores.

Apatite is not important as an ore of phosphate. In the Adirondacks it occurs with magnetite in deposits formed by magmatic segregation (page 337). The production from these deposits is small. In Ontario and Quebec, notably at Templeton,

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[1] Richards, R. W., and Mansfield, G. R.: Preliminary Report on a Portion of the Idaho Phosphate Reserve. U. S. Geol. Survey *Bull.* 470, p. 371, 1911. Blackwelder, Eliot: Origin of Rocky Mountain Phosphate Deposits. Geol. Soc. America *Bull.*, vol. 26, p. 100, 1916.

Quebec,[1] considerable deposits of apatite are found with pyroxene, mica, and calcite in what appears to be a contact-metamorphic or nearly related deposit. The Canadian apatites have been almost driven from the market by the higher-grade phosphate rock, and now the deposits are worked principally for mica.

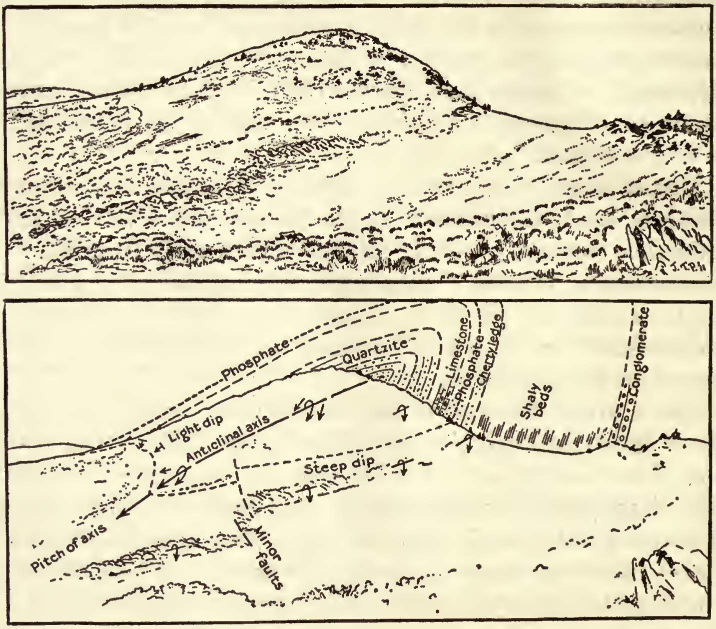

Fig. 207.—View of phosphate mountain near Melrose, Mont., looking from the direction of Melrose, with a diagrammatic section showing the geologic structure. (*After Gale, U. S. Geol. Survey.*)

Apatite is the most abundant rock-making mineral that contains phosphorus and doubtless is the chief original source of the element. Clarke[2] cites many analyses of river water which carry from a trace to 1.6 per cent. PO_4. Sea water, on the other hand, contains only traces of phosphorus. It is removed to form the bones of fishes and other aquatic vertebrates and is precipitated in phosphatic nodules that are found on the sea bottom. It is

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[1] Penrose, R. A. F., Jr.: Nature and Origin of Deposits of Phosphate of Lime. U. S. Geol. Survey *Bull.* 46, pp. 34–39, 1888.

Cirkel, Fritz: Mica; Its Occurrence, Exploitation, and Uses, pp. 1–148. Canada Dept. Mines, Mines Branch, 1905.

[2] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, pp. 75–106, 1916.

probably precipitated also by the metasomatic replacement of lime carbonate shells.

The deposits of phosphate rock in Utah, Idaho, Wyoming, and Montana[1] are the most extensive known. These deposits, although of high grade, are not now worked except on a small scale. But they will probably be worked extensively within a few decades, when western soils will require fertilizers, or as soon as low freight rates permit shipment. The deposits are principally in the limestones of the Pennsylvanian (upper Carboniferous). They are sedimentary beds associated with limestones, sandstones, and shales and are but little altered by surface leaching.

MAGNESIAN MINERALS

Olivine	$(FeMg)_2.SiO_4$
Enstatite	$(FeMg).SiO_3$
Serpentine	$H_4Mg_3.Si_2O_9$
Magnesite	$MgCO_3$
Tremolite	$CaMg_3.Si_4O_{12}$
Talc	$H_2Mg_3.Si_4O_{12}$
Meerschaum	$H_4Mg_2.Si_3O_{10}$

Olivine and Serpentine.—Of the magnesian minerals olivine generally has no marketable value, though some varieties are used in a small way as gem material. It is, however, an important source of serpentine and other magnesian minerals. It is the principal constituent of peridotites and is present in many other basic rocks that alter to serpentine. It is a valuable protore of iron.

Olivine is one of the most unstable minerals and changes into serpentine with great facility. Peridotites and other basic rocks that in hand specimens appear to be perfectly fresh are almost universally found, when examined microscopically, to be serpentinized along cracks of olivine. As secondary products, both talc and serpentine are formed at very great depths. In California canyons thousands of feet deep expose serpentine

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[1] Richards, R. W., and Mansfield, G. R.: Preliminary Report on a Portion of the Idaho Phosphate Reserve. U. S. Geol. Survey *Bull.* 470, p. 371, 1910.

Gale, H. S.: Rock Phosphate near Melrose, Mont. *Idem*, p. 440.

Blackwelder, Eliot: A Reconnaissance of the Phosphate Deposits of Western Wyoming. *Idem*, p. 452.

rocks. Either they were formed far below the surface, or alteration was more rapid than erosion, which in the surroundings is almost incredible. Lindgren[1] has suggested that olivine has changed to serpentine through the agency of ascending waters associated with igneous intrusives. The alteration of olivine to serpentine involves no great chemical change, as is indicated by the following equation:[2]

$$\underset{\text{Forsterite}}{2Mg_2SiO_4} + CO_2 + 2H_2O = \underset{\text{Serpentine}}{H_4Mg_3Si_2O_9} + \underset{\text{Magnesite}}{MgCO_3}$$

Serpentine develops from pyroxenic rocks that have replaced limestones, and also in ferromagnesian schists. The formation of serpentine is attended by increase of volume, and some serpentine rocks disintegrate readily when piled in dumps. Thus diamond-bearing serpentines in South Africa crumble down in a few months. Serpentine, particularly the green translucent variety, is used for ornamental purposes. The asbestiform varieties of serpentine are mentioned on page 581.

Magnesite.—Magnesite develops from olivine and serpentine, in part after the manner indicated in the equation above. It occurs in veins and fractured zones, filling cavities and replacing the serpentine wall rock. Commonly associated minerals are chalcedony and quartz. The change is probably effected through the agency of carbonated water, as indicated by the equation below, serpentine yielding magnesite and silica.

$$H_4Mg_3Si_2O_9 + 3CO_2 = 3MgCO_3 + 2H_2O + 2SiO_2,$$

Considerable deposits are found in California,[3] especially in the Coast Range. Almost if not quite invariably the magnesite is associated with serpentine. The deposits of the United States supplied about 30,499 tons in 1915, valued at $274,491. This, however, is only a small part of the magnesite used in this country. Imports come from Austria and Greece.

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[1] Lindgren, Waldemar: "Mineral Deposits," p. 343, New York, 1913.

[2] For simplicity I have used forsterite, the magnesium olivine, free from iron. Fayalite (Fe_2SiO_4) is the corresponding iron olivine. Both species are comparatively rare. Common olivine generally contains both iron and magnesium.

[3] Hess, F. L.: The Magnesite Deposits of California. U. S. Geol. Survey *Bull.* 355, 1908.

Gale, H. S.: Late Developments of Magnesite Deposits in California and Nevada. U. S. Geol. Survey *Bull.* 540, pp. 483–520, 1912.

Magnesite is used principally for making refractory brick, for smelting, for packing steam pipes, and in the manufacture of paper, carbon dioxide, oxychloride cement, medicines, etc.

Talc.—Tremolite, enstatite, and other magnesian minerals break down readily, forming talc. The reactions, according to Clarke,[1] are as follows:

$$CaMg_3Si_4O_{12} + H_2O + CO_2 = H_2Mg_3Si_4O_{12} + CaCO_3$$
$$Mg_4Si_4O_{12} + H_2O + CO_2 = H_2Mg_3Si_4O_{12} + MgCO_3$$

Compact and impure talc is called soapstone. In many places talc is formed by the alteration of tremolite-bearing limestone or from basic igneous rocks. Talc is found in schists or dynamically metamorphosed rocks.[2] Dynamic metamorphism is not necessary for its development, however, as it is found also in rocks that are not highly schistose.

Talc and soapstone are used as refractories, in laboratory tables, gas burners, electric insulators, etc. Ground to powder they are used in making paper, paint, toilet powder, and dynamite. The United States in 1915 produced 186,891 tons of talc and soapstone, valued at $1,891,582.

Meerschaum.—Meerschaum is probably derived from serpentine and from impure dolomites. Its uses for smokers' articles are well known. Most of it is imported from Asia Minor. In New Mexico it forms veins and balls in cherty limestone.[3]

ASBESTOS

Asbestos is a trade term that is applied to minerals that are fibrous and poor conductors of heat and that may be used in making certain products for protection against fire. Most of them are magnesian minerals. Serpentine ($H_4Mg_3Si_2O_9$), amphibole ($Ca(Mg,Fe)_3(SiO_3)_4$), anthophyllite ($[Mg,Fe]SiO_3$), and crocidolite ($NaFeSi_2O_6.FeSiO_3$) have asbestiform varieties.

Several types of asbestos are recognized—cross-fiber, slip-fiber, and mass-fiber. The cross-fiber asbestos occurs in veins as much as several inches wide, and the fibers are about normal

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[1] Clarke, F. W.: The Data of Geochemistry, 3d ed. U. S. Geol. Survey *Bull.* 616, p. 415, 1916.

[2] Diller, J. S.: U. S. Geol. Survey *Mineral Resources*, 1908, part 2, pp. 869–878.

[3] Sterrett, D. B.: Meerschaum in New Mexico. U. S. Geol. Survey *Bull.* 340, pp. 466–473, 1908.

to the walls of veins. The slip-fiber occurs on slipping planes, and the fibers are parallel to the planes of movement. Mass-fiber is found as masses not occupying veins or slipping planes, and the threads are arranged haphazard or are radiating. Most of the cross-fiber asbestos, which is the highest grade, is chrysotile. Much of the mass-fiber is anthophyllite.

As a rule much waste rock is mined with asbestos. The ore is crushed and separated, usually by means of an air blast.

Serpentine asbestos is formed by the alteration of peridotite or certain other rocks. The highest-grade asbestos deposits are veinlets in serpentine. It is believed that they have been formed through the agency of waters that coursed through cracks and fissures, either hot waters soon after the rocks had formed or surface waters later, when the rocks were eroded.

The most productive deposits of asbestos in North America are at Thetford, Quebec,[1] in a belt of igneous rocks that extends southwestward into northern Vermont[2] (see Fig. 208). The asbestos occurs as cross-fiber veins, closely spaced in a serpentine that has probably been formed by alteration from peridotite. The veinlets, which are from a fraction of an inch to several inches thick, are believed to be alteration products of the igneous rocks in which they are found. Veins of chrysotile asbestos in serpentine are worked in Orleans and Lamoille counties, Vermont. Near Casper, Wyo.,[3] veins of cross-fiber asbestos occur in serpentine, which also is probably an alteration product of peridotite.

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[1] Cirkel, Fritz: Chrysotile Asbestos, Its Occurrence, Exploitation, Milling, and Uses, 2d ed. Canada Dept. Mines, Mines Branch, 1910.

Dresser, J. A.: On the Asbestos Deposits of the Eastern Townships of Quebec. *Econ. Geol.*, vol. 4, p. 130, 1909.

Ells, R. W.: *Bulletin* on Asbestos, Canada Geol. Survey, 1903.

[2] Diller, J. S.: The Types and Modes of Occurrence of Asbestos in the United States. Canadian Min. Inst. *Quart. Bull.* No. 13, pp. 45–58, February, 1911.

Marsters, V. F.: Petrography of the Amphibolite, Serpentine, and Associated Asbestos Deposits of Belvedere Mountain, Vermont. Geol. Soc. America *Bull.*, vol. 16, pp. 419–446, 1905.

Richardson, C. H.: Asbestos in Vermont. Vermont State Geologist *Seventh Rept.*, pp. 315–330, 1910.

[3] Lakes, Arthur: The Wyoming Asbestos Deposits and Mills. *Min. Sci.*, October 28, 1909.

Diller, J. S.: The Types, Modes of Occurrence, and Important Deposits of Asbestos in the United States. U. S. Geol. Survey *Bull.* 470, pp. 512–516, 1911.

In the Grand Canyon of Arizona asbestos occurs with serpentine in limestone. Diller considers it to be derived from material of sedimentary origin. The asbestos rocks are near an intruding diabase sill, and the parent olivine minerals may have been formed by contact-metamorphic processes.

In Idaho, about 14 miles southeast of Kamiah, ledges of anthophyllite rock are found intruded in mica schist. This rock is quarried and shipped to Spokane, Wash.

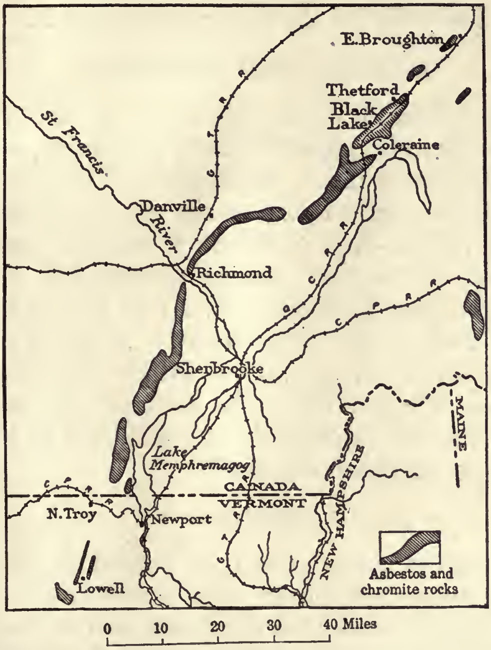

FIG. 208.—Map showing location of asbestos deposits in northern Vermont and adjoining portion of Canada. (*After Diller, U. S. Geol. Survey.*)

Most of the asbestos produced in the United States is mined in Georgia. At Sall Mountain, Ga., according to Diller, anthophyllite asbestos occurs in lenticular masses in gneiss, which is believed to be an altered igneous rock. Near Bedford, Va., there are deposits of mass-fiber presumably derived from basic rocks.

The production of asbestos in the United States is small. In 1915 it amounted to 1,731 short tons, valued at $76,952. The value of the annual Canadian output is about $3,000,000. Asbestos is used for making fireproof theater curtains, ropes, clothing, etc. When felted it is a good nonconductor of heat and electricity and finds many uses as an insulator. The lower grades are mixed with cement and manufactured into fireproof shingles. These are cheap and for some purposes are superior to tile and slate. Asbestos plaster is used in theaters to deaden noise. Boards are made of asbestos and cement. The demand is increasing, especially for the low-priced materials.[1]

MONAZITE AND XENOTIME

Monazite is normally cerium phosphate ($CePO_4$), but rare-earth metals—thorium, praseodymium, lanthanum, neodymium—are generally present in it. Xenotime ($YtPO_4$) is a phosphate of yttria, with rare earths of the cerium group. These minerals are exploited for the rare earths they contain, especially for thorium, which is used for making glowers and mantles for lights. The principal production[2] is derived from the Carolinas, east of the Blue Ridge. The country is an area of gneiss, schist, and granite, cut by various intrusive rocks, including extensive dikes of pegmatite. The monazite is mined mainly from placers, but some is mined from pegmatized gneiss in place, especially where the gneiss has rotted.

ZIRCON

Small amounts of zircon (ZrO_2) are present in many igneous rocks. Some pegmatites contain considerable amounts. Zircon resists weathering processes and is concentrated in stream gravels derived from zircon-bearing rocks. In the Carolinas zircon is associated with monazite in gravels. Near Zirconia, Henderson County, North Carolina, zircon is obtained by washing the decomposed croppings of a pegmatite dike.[3] Zircon-bearing pegmatites occur also near Cash in the Wichita Mountains, Oklahoma.[4]

Zircon is used for the manufacture of zirconium compounds, which are used in making glowers for the Nernst electric light.

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[1] DILLER, J. S.: U. S. Geol. Survey *Mineral Resources*, 1911, part 2, p. 995, 1912.

[2] PRATT, J. H., and STERRETT, D. B.: Monazite and Monazite Mining in the Carolinas. Am. Inst. Min. Eng. *Trans.*, vol. 40, pp. 488–511, 1909.

[3] STERRETT, D. B.: Monazite and Zircon. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 1193–1196, 1912.

[4] STERRETT, D. B.: Monazite and Zircon. U. S. Geol. Survey *Mineral Resources*, 1907, part 2, p. 792, 1908.

WATER

Occurrence.—Water (H_2O) is essential for animal and vegetable life, and it plays a part in the genesis of all minerals. A part of the rain water that falls upon the earth soaks into the ground and, where openings are available, reissues as springs. The distribution and movements of ground water are mentioned under weathering and also in the discussion of the enrichment of ores. Nearly everywhere the ground contains some water, but the amount is exceedingly variable, depending on the climate, the structure of the rocks, the distribution of fissures, etc.

Below the vadose zone (page 132) the rocks are generally saturated with water. At greater depths, however, the rocks because of pressure are tight, and water if present is nearly static. Estimates of the amount of water in the earth's crust,[1] stated in terms of the thickness of a uniform blanket of water spread over the surface, range from less than 100 feet to nearly 1,000 feet.

Almost all deep mines encounter more or less water. Wells sunk for water frequently encounter a supply only a few feet below the surface. Some, however, go hundreds of feet to water, the depth depending on local conditions. On the flood plains of rivers water is generally reached near the surface. Many wells in glacial drift encounter water at shallow depths. Some deep borings are dry.

Artesian Water.—Deep borings encountering abundant water supply are commonly termed artesian wells (from Artois, France, where wells of this sort have long been used). Originally, however, this term was applied only to flowing wells. The conditions that are favorable to the development of an artesian circulation are (1) a porous bed of size sufficient to serve as a carrier and reservoir, (2) an impervious bed above it, (3) a collecting area higher than the point of issue.[2]

Sandstones and gravels are good water carriers. The total pore space of such rocks commonly amounts to 10 per cent. or more. Because of their storage capacity thick sandstones are

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[1] Van Hise, C. R.: A Treatise on Metamorphism. U. S. Geol. Survey *Mon.* 47, pp. 123–657, 1904.

Fuller, M. L.: The Amount of Free Water in the Earth's Crust. U. S. Geol. Survey *Water-Supply Paper*, 160, 1906.

[2] Chamberlin, T. C.: Requisite and Qualifying Conditions of Artesian Wells. U. S. Geol. Survey *Fifth Ann. Rept.*, pp. 131–173, 1884.

better carriers than thin sandstones. Fractured limestones or other fractured rocks may be carriers or reservoirs of water. Amygdaloidal lavas have high pore space and may carry water, but because their openings are not connected they are generally inferior to sandstones. The shafts that penetrate many tilted vesicular flows at copper mines of Keweenaw Point, Mich., are dry in the deeper levels.

For an artesian flow it is necessary that the pervious beds be capped by impervious or nearly impervious rocks (Figs. 209, 210), for otherwise the water would escape and the water pressure would be lowered to a point where water would not rise in openings. In general shale forms the best cap above the pervious beds. The character of the rocks below the water carrier is not important if such rocks do not crop out below the carrier. If the underlying rocks are impervious they will hold the water in; if they are pervious and have no outlet they will be filled with stagnant water that will prevent the downward escape of water in the carrier. The water-bearing bed should be exposed at a point above the point of issue. The water will not rise as high as the point of entry because of loss of pressure due to friction. In crystalline rocks, such as granites and schists, where joints and fissures are numerous and closely spaced, these openings may serve as reservoirs of underground water. In general it is necessary to pump the water, and as a rule the flow is not great. In some mines in crystalline rocks, however, the flow of water is very large after numerous drifts and crosscuts have been run into the surrounding rocks. As a rule small pumps can handle the water

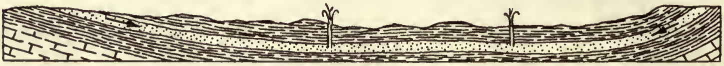

Fig. 209.—Diagram illustrating chief requisite conditions of artesian wells. (*After T. C. Chamberlin, U. S. Geol. Survey.*)

Fig. 210.—Diagram illustrating the thinning out of a porous bed between two impervious beds. (*After T. C. Chamberlin, U. S. Geol. Survey.*)

encountered in sinking shafts in crystalline rocks, and unless master fissures are cut, the amount per foot of opening, of water flowing to the shaft decreases a few hundred feet below the surface.[1]

Mineral Waters.—Natural waters are rarely pure. Even rain water carries some mineral salts, as well as carbon dioxide and a little oxygen. Many minerals are attacked by water, and as rain water percolates through soil or rocks it gathers mineral matter, which it carries in solution.

Mineral waters are grouped as table and medicinal waters. Table waters are generally not high in mineral salts; if they were their taste and physiologic effects would render them unpopular. Waters low in mineral salts and high in carbonic acid are highly prized for table use because of the palatable quality imparted by the acid. Nearly all the carbonated waters of the trade are simply pure water or water of low salinity artificially carbonated. The United States in 1915 produced 52,113,503 gallons of mineral waters valued at $5,138,794.[1]

Medicinal waters are prized because of their therapeutic qualities. Waters carrying less than 150 parts per million of total mineral matter are classed as "low in mineral matter,"[2] those carrying more than 500 parts are "high," and those carrying more than 2,000 parts are "very high." As a rule waters that contain more than 1,000 parts of salts per million are not palatable, yet waters with 2,500 parts per million may be used for many days without discomfort, and some persons can withstand waters with more than 3,300 parts per million. Waters with as much as 5,000 parts per million are inimical to health.

It has been questioned whether the mineral waters of some resorts possess the therapeutic effects that are ascribed to them. Some of these waters carry a mineral content lower than that of city supplies. Some of the "cures" reported to have been effected at these resorts are doubtless due to changes in the environment and manner of living of the patients and to copious drinking of water, which under some conditions is beneficial. Lithium salts are commonly supposed to relieve uric acid poisoning, but this

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[1] Discussions of the water supply of the United States are given in the water-supply papers of the United States Geological Survey.

[2] DOLE, R. B.: The Concentration of Mineral Water in Relation to Therapeutic Activity. U. S. Geol. Survey *Mineral Resources*, 1911, part 2, pp. 1175–1192, 1912.

has been questioned. Sulphates in moderately large doses are cathartic. Magnesium carbonate and bicarbonate are alkaline and if given in small doses will correct acidity of the stomach. Boron salts are antiseptic, and some barium salts are supposed to correct arterial troubles. Iron salts are tonic. Arsenic salts above small amounts are poison.

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