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State of Connecticut
State Geological and Natural History Survey
BULLETIN No. 13

THE LITHOLOGY OF CONNECTICUT

By
JOSEPH BARRELL, E.M., Ph.D.
Professor of Structural Geology in Yale University
and
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Preface.

To the student who is beginning the study of geology, and particularly to the one who is seeking to understand the nature and significance of the rock formations of his locality, the most difficult step in his progress is to correctly apply the facts and principles of the text to the explanation of the local geological features. The purpose of this Bulletin and of the Connecticut Educational Series of Rocks is to assist in overcoming this difficulty.

It is believed that such a collection supplemented by an explanatory bulletin will be particularly useful to the teachers of natural science in the high schools and other educational institutions of the state. But, as the number of sets of rock specimens is necessarily limited, and the Bulletin will consequently have a distribution much wider than the collections, the first part has been made an independent work on the "Outlines of Lithology." It is thought that this part, especially if it is supplemented by the purchase or collection of a small set of the common rock-making minerals and some rock specimens, may be of assistance to those interested in the subject of out-of-doors geology but without a previous training in mineralogy and lithology. Some knowledge of elementary chemistry and geology is, however, desirable.

In most elementary treatises on both mineralogy and lithology the end sought is merely the identification of the mineral or rock and knowledge of the composition. This method of treatment tends to make these closed subjects, not naturally leading to and throwing light on other branches of knowledge. In the present work it is sought to obviate this tendency by introducing, in connection with the description of both minerals and rocks, considerable matter in regard to the origin, history, and significance of the objects in question. The presentation of these geological relations leads naturally from the study of mineralogy to that of lithology and thence to geology.

The better to attain these ends, the Bulletin is made as distinct in what it omits as in what it includes. No more mineralogy is introduced than is necessary for determining and understanding the nature of rocks, and no more lithology is given than is necessary for the study of rocks without a microscope. Information which has been derived from chemical, microscopical, or geological investigation is freely introduced where it is necessary for an understanding of the origin and significance of a rock; but all discriminations between rocks which depend upon chemical or microscopical distinctions are carefully avoided, and the systems of classification which have been employed are made to conform to that requirement. Thus the student, in order to properly classify and understand any specimen within the limits of this Bulletin, need not rely on any characters which are doubtful or beyond his reach to determine. It is the attempt to dogmatically enforce distinctions which the student cannot determine and to classify rocks on the basis of obscure characters, which is responsible for the empirical and unscientific state of the study of lithology as illustrated in some text-books and as too frequently taught.

The second part of the Bulletin has been made fairly independent of the first half, even at the risk of a slight degree of repetition, as this saves the necessity of turning back and forth from one place to another; and for those who wish to study the rock collection carefully the two parts will be found mutually supplementary. The rock specimens have, further, been described with considerable fullness, as it is desirable to encourage the closest possible examination, and furthermore to place on record such points of significance in regard to these types as sometimes can only be determined by examination of the rock in thin section by the compound polarizing microscope.

The sources of information which have been most largely drawn upon for the first part, written in 1907, are as follows: —

Analyses of Rocks, Bull. No. 228, U. S. Geol. Surv.; by F. W. Clarke.

A System of Mineralogy; by E. S. Dana.

A Treatise on Metamorphism, Mono. No. 47, U. S. Geol. Surv.; by C. R. Van Hise.

A Handbook of Rocks; by J. F. Kemp.

Quantitative Classification of Igneous Rocks; by Cross, Iddings, Pirsson, and Washington.

The method of treatment, the arrangement of the tables, and some details in the systems of classification are, however, largely original.

The collecting of the specimens in the sets of the Connecticut Educational Series of Rocks was begun in the summer of 1905, by Dr. Freeman Ward, Instructor in Geology in the Sheffield Scientific School, Yale University; and was completed in the summer of 1906 by Dr. G. F. Loughlin, assisted by Dr. D. L. Randall, then graduate student and Assistant in Chemistry in the Academic Department of Yale University. Acknowledgments and thanks are due to Mr. C. A. Fiske, of South Killingly, who collected the specimens of Plainfield quartz schist at his own expense, and to Mr. Hinckley, Superintendent of the Norcross Brothers' Stony Creek quarry, who donated for the Company the handsome specimens of the Stony Creek granite. Since this manuscript was written the volume on "Rocks and Rock Minerals" by Professor L. V. Pirsson of the Sheffield Scientific School has appeared. This work, "A Manual of the Elements of Petrology without the Use of the Microscope," is more comprehensive than the present Bulletin and planned for those who have had college courses in chemistry, mineralogy, and geology. Still more extensive works by Harker and Iddings respectively have been published during the past year, 1909. For those who wish to look up the distinctions of rock species in greater detail, to attain a more professional power in the subject, or to understand the present advance problems in petrology these three works are recommended.

JOSEPH BARRELL,
GERALD FRANCIS LOUGHLIN.

Table of Contents.

Part I.

AN OUTLINE OF LITHOLOGY.

PAGE.

Introduction 17

CHAPTER I. THE CHEMISTRY OF ROCKS . . . 20
Preliminary statement 20
Composition of the earth's crust 20
Chemical characteristics of the common elements . 22
Association of the element 26

CHAPTER II. THE MINERALOGY OF ROCKS . . . 27
Igneous, sedimentary, and metamorphic (anamorphic) rocks 27
The nature of minerals 28
Chemical nature 28
Physical nature 30
The methods of identifying minerals . . . 31
The physical properties of minerals . . . 32
Hardness 32
Cleavage 33
Color and streak 34
Other physical characteristics . . . 35
Description of minerals 35
Introduction 35
Common minerals of igneous and metamorphic (anamorphic) rocks 36
Ratio of occurrence 36
Notes supplemental to Table I. . . 37
Minerals resulting from rock decay (katamorphism) 45
Relations of minerals to rock decay . . 45
Climate and topography as factors in rock decay 46
Notes supplemental to Table II. . . 47
Some minerals characteristic of metamorphic (anamorphic) rocks 57
Preliminary statement 57
Notes supplemental to Table III. . . 58

PAGE.

CHAPTER III. THE IGNEOUS ROCKS 65
Variations in chemical composition . . . 65
Acidic, intermediate, and basic divisions . . 65
Magmatic differentiation and petrographic provinces 67
Modes of mineral aggregation 69
Definitions of textures 69
Origin and significance of textures . . . 70
Structures 74
Spherical structures 74
Parallel structures 75
Fragmental structures 76
Massive structure 76
The principles of classification 77
A megascopic classification of igneous rocks . . 79
Explanatory statement 79
The fragmental igneous rocks . . . 80
The rock glasses 81
The aphanitic lavas 82
The porphyries 8
The microphanerites 85
The phanerites 87

CHAPTER IV. THE SEDIMENTARY ROCKS . . . 90
Introductory statement . . . . , 90
Textures 90
Structures 92
The principles of classification 94
Descriptions of sedimentary rocks . . . 97
Mechanical sediments 97
Visibly granular 97
Invisibly granular 98
Chemical sediments 99
Calcareous rocks . . . , . . 99
Calcareous rocks of organic origin . . 99
Calcareous rocks of inorganic origin . 101
Siliceous rocks of chemical origin . . 103
Organic 103
Inorganic 104
Carbonaceous rocks 105
Coal series 106
Petroleum series 109
Iron ores 109
Evaporation products 110

PAGE.

CHAPTER V. THE METAMORPHIC (ANAMORPHIC) ROCKS . 111
Introductory statement 111
The principles of classification . . . 113
Textures 114
Structures 114
Conditions of metamorphism . . . 116
Dynamic metamorphism 116
Thermal metamorphism 117
Hydrothermal metamorphism . . . 117
Compositional factors in classification . . 118
A classification and description of metamorphic rocks 119
Rocks made by dominant dynamic metamorphism 119
Gneisses 119
Crystalline schists 121
Marbles 124
Rocks made by dominant thermal metamorphism 125
Silica rocks 125
Silica-alumina rocks 126
Lime-magnesia rocks 127
Iron ores 127
Mixed types 128
Rocks made by dominant hydrothermal metamorphism 128
Anhydrous rocks 128
Hydrous rocks 129

Part II.

DESCRIPTIONS OF THE CONNECTICUT EDUCATIONAL SERIES OF ROCKS.

PAGE.

Introduction 135

CHAPTER I. RECENT AND PLEISTOCENE FORMATIONS . 137
Residual materials 137
Kaolin. Sharon 138
Limonite. Ore Hill, Salisbury . . . 139
Transported materials 141
Till. Westville, New Haven 141
Glaciated pebble. Westville, New Haven . . 143
River gravel, Glacial period. Westville, New Haven 144
Sand, Glacial period. Westville, New Haven . 146
Clay, Glacial period. Quinnipiac Valley, Hamden 146
Clay concretions. Elmwood, West Hartford . 148
Beach pebble. Niantic, East Lyme . . . 150
Magnetite and garnet sand. Savin Rock, Orange 151
Organic deposits 152
Peat. Quinnipiac Valley, Hamden . . . 152

CHAPTER II. THE OLDER SEDIMENTARY FORMATIONS . 154
Mechanical deposits 154
Conglomerate. Portland 154
Arkose. Fair Haven, New Haven . . . 156
Red shale. Portland 157
Black shale. Lake Saltonstall, Branford . . 158

CHAPTER III. THE IGNEOUS FORMATIONS . . . 159
The granites 159
Thomaston granite. Thomaston . . . 159
Westerly granite. Niantic, East Lyme . . 161
Stony Creek granite. Stony Creek, Branford . 162
The basic rocks 165
Preston gabbro-diorite. Preston 165
Triassic diabase. West Rock, New Haven . 167
Triassic basalt. Meriden 169

PAGE.

CHAPTER IV. THE METAMORPHIC FORMATIONS . . 171
The gneisses 171
Gneisses of igneous origin 171
Prospect porphyritic granite-gneiss. Derby . 171
Danbury granodiorite-gneiss. Stevenson, Monroe 173
Stony Creek granite-gneiss. Hoadley Point, Guilford 174
Maromas granite-gneiss. Ben Venue Quarry, Middletown 175
Bristol granite-gneiss. Bristol . . . 176
Gneisses of sedimentary origin . . . 178
Putnam gneiss. Putnam . . . 178
Gneisses of unknown origin 180
Becket gneiss. West Cornwall . . . 180
The schists 181
Schists of igneous origin 182
Hornblende biotite schist. Rockville . . 182
Milford chlorite schist. Savin Rock, Orange 184
Schists of sedimentary origin, and quartzite . 185
Poughquag quartzite. North Canaan . . 185
Plainfield quartz schist. South Killingly, Killingly 187
Orange phyllite. Derby trolley cut, Orange . 188
Hartland (Hoosac) schist. Roaring Brook, Southington 189
Berkshire schist. Salisbury . . . 191
Bolton schist. Vernon 192
Muscovite variety 192
Quartzose variety 192
Carbonate rocks 194
Stockbridge tremolitic marble. East Canaan, North Canaan 194

CHAPTER V. PEGMATITES AND VEINSTONES . . 197
Pegmatites 197
Pegmatite. West Cornwall, Cornwall . . 197
Veinstones 199
Lantern Hill quartz rock. Lantern Hill, North Stonington 199
Siderite. Mine Hill, Roxbury . . . 201

Part I

An Outline of Lithology

BY

JOSEPH BARRELL

An Outline of Lithology.

INTRODUCTION.

A *rock* may be defined as any mineral or aggregate of minerals occurring in masses of considerable size. Under this definition unusual or local aggregates of minerals do not form rocks, while, on the contrary, ice, which is not commonly thought of as a rock, is such in all essential characters, and in certain regions becomes an important surface formation. Rocks are commonly somewhat firmly consolidated, and this also would on first consideration be regarded as an essential; yet it is seen that no line of separation can be drawn between such solid rocks as those into which the sands and muds of distant geological ages have been transformed, and the semi-consolidated deposits of more recent times, or the sediments now accumulating. Neither can any line be justly drawn excluding from the category of rock those bodies of molten material which may remain fluid or semi-fluid for long periods of time within the earth; and admitting only the solid bodies into which they turn, upon extrusion as lavas, or upon slowly crystallizing at a depth. The great differences in physical properties, however, between the fluid and solid states make it convenient to call the molten forms *magma,* while the more familiar solid forms are known as *rock.* The atmosphere and ocean are by many geologists thought to be largely if not wholly the emanations of volatile materials through all geologic time up to and including the present, from molten rocks which have worked to or near the surface of the earth. Under this view the gaseous and liquid envelopes of the earth are to be looked upon as the separated and still unconsolidated portions of magmas, destined, after further geologic ages and the ultimate decay of the solar energy, to become likewise a part of the solid crust.

Lithology (the science of stones) is that branch of knowledge which deals with the characteristics and identifying features of

the various rocks, and, further, discusses the conditions of origin and the subsequent changes to which rock masses are subject. Two related and more or less synonymous words are petrography and petrology, the first meaning, literally, the description of rocks, the second the science of rocks. In recent years these words have been used with somewhat different meanings, lithology referring to the general science of rocks pursued especially in the laboratory in a broad way and without going into the refined modes of investigation or refined distinctions between species. Petrography, however, is the word which should be used when technical descriptions and discussions of rocks are given. Petrology is etymologically the most inclusive of the terms, embracing what is here given as the province of lithology and that of petrography and including a study of rocks in their field relations. All students interested in minerals and rocks, or wishing to obtain a real as contrasted with a mere text-book knowledge of geology, should study the elements of lithology. Petrology, however, is a particular branch of geology demanding special training; while lithology, as here presented, requires no previous training of any sort but merely an earnest effort.

The parts of lithology which are of more immediate concern are those which deal with the familiar kinds of rocks making up the outer solid crust of the earth, and the present work is restricted to such a discussion as is necessary to determine those species which occur within the state of Connecticut and to describe their characteristics. In order, however, to appreciate the place of these rock types in the scheme of rock classification, a general outline of the whole subject is given in the first part, with brief discussions of all important kinds, whether they occur in Connecticut or not. In this way a general view of the subject may be attained. This has been thought the more desirable since there is no text-book of lithology published which reduces the technical terms and refined distinctions to a degree at which the work is usable without excessive effort by the amateur. The text-books of geology, on the other hand, can devote so little space to the description and means of identification of rock types that, while understandable, they can hardly be applied in the field without considerable amplification by a teacher.

An understanding of the common types of rocks and an ability to identify them are of use in three broadly different ways. First, may be mentioned economic lithology, dealing with building stone, cement materials, clay beds, and other deposits worked by man for his uses. Second, stands the relation of rocks to the soil; the character of the latter, determining its value for agriculture, depending largely upon the rocks from which it has been derived. The third use of rocks lies in their intellectual interest. Something should be known of them because they as component portions of the earth, or the mantle of soil derived from them, are ever before our eyes and should also be before our minds. They also serve a higher use as the alphabet in the study of earth history. For such a purpose it is necessary to determine the mode of origin of the various kinds. When this is known, each rock formation becomes a piece of geologic history, and this information carefully fitted together from various parts of the earth has given rise to the science of geology.

The principles of a science are incorporated in books, but it should never be forgotten that the text is merely a means to an end, and that each student should finally become as independent as possible of the printed page, and learn to recognize the things in nature and to see for himself the meanings.

The present Bulletin is written to accompany the Connecticut Educational Rock Series of forty specimens, and the plan is to give a sufficient introduction to the subject, that the specimens may be intelligently studied. The latter have been collected to illustrate the geology of the state, and have been selected from both consolidated and unconsolidated materials to illustrate various typical or valuable geologic formations. The present Bulletin and suite of specimens therefore supplement Bulletin No. 6, a Manual of the Geology of Connecticut by Professors Rice and Gregory, and Bulletin No. 7, a Preliminary Geological Map of Connecticut by Professor Gregory and Dr. Robinson. For those with little or no previous training in geology this Bulletin should be studied previously to the other two and after the study of some elementary text-book in geology. A great aid to its understanding for those unacquainted with mineralogy would be found in the purchase of a small and cheap set of the common minerals such as are supplied by various mineral dealers.

Chapter I.

THE CHEMISTRY OF ROCKS.

PRELIMINARY STATEMENT.

Some knowledge of chemistry is presupposed in the study of minerals and rocks, but certain chemical principles which bear on the subject may here be repeated.

An *element* is the simplest substance with which the chemist has to deal. All more complex substances may, with greater or less difficulty, be broken up by heat, electricity, or chemical reagents; but no element is known to have its integrity destroyed to an appreciable degree by these means. Although the elements are for these reasons the units of the chemist, it does not by any means follow that they are the fundamental units of matter, and the phenomena of radio-activity point to the spontaneous disintegration of certain of the heavier elements; a breaking down which is so slow, however, that the entire duration of the earth, through probably at least a hundred million years, has not sufficed for the disappearance of the parents (uranium and thorium) of the radio-active elements from the earth's crust. These are activities, however, which do not concern the subject in hand.

Although the discoveries of recent years have raised the number of elements known to exist to 78, there are relatively few of these which enter to an appreciable extent into the composition of the earth's crust, even such familiar elements as copper, zinc, and nickel forming a negligible fraction of the crust and becoming available to man only on account of their rare and local concentration into ore deposits.

COMPOSITION OF THE EARTH'S CRUST.

A list of the elements which are of importance in the composition of rocks, and the estimated percentage in which they occur in the earth's crust, excluding the ocean and atmosphere, is as follows:—*

* F. W. Clarke. Bulletin No. 228, U. S. Geol. Surv., 1904, p. 19.

PERCENTAGES OF COMMON ELEMENTS IN EARTH'S CRUST.

Element.	Symbol.	Per cent.
Oxygen	O	47.09
Silicon	Si	28.23
Aluminum	Al	7.99
Iron	Fe	4.46
Magnesium	Mg	2.46
Calcium	Ca	3.43
Sodium	Na	2.53
Potassium	K	2.44
		98.63

Of the less common elements those which are most apt to occur in the ordinary rocks in noticeable combinations are as follows: —

PERCENTAGES OF LESS COMMON ELEMENTS IN EARTH'S CRUST.

Element.	Symbol.	Per cent.
Hydrogen	H	.17
Titanium	Ti	.43
Carbon	C	.14*
Phosphorus	P	.11
Sulphur	S	.11
Chlorine	Cl	.07*
		1.03

All of these elements except occasionally carbon, sulphur, and iron occur in the earth's crust only in combination with one or more other elements, forming definite compounds known as minerals. Some, such as phosphorus and iron, may be isolated by chemical processes from the other elements with relatively little difficulty. Others, however, strongly resist separation from their compounds. It is noted that by far the most abundant element in the crust is oxygen, which in its free form is a gas and as such consitutes 21 per cent. by volume of the atmosphere. More than any other element it tends to enter into combination with others, only a few metals and gases showing little or no tendency to combine with oxygen. The rock-making elements therefore are commonly found in various combinations with oxygen and other

* The percentages assigned to C and Cl are nothing more than very rough approximations.

elements. When with oxygen alone the compound is known as an oxide. In quantitative chemical analyses, an element is rarely reduced to the elemental state, but is commonly transformed in the laboratory into some known compound of which it forms a definite percentage, and in many cases these known compounds are oxides. In reports of chemical analyses of rocks, the elements are therefore not commonly listed as such, but as oxides. Knowing the atomic weights of the elements and the ratio of combination, the amount of an element present may be readily calculated if necessary when the amount of its oxide is known.

A table of the average composition of the earth's crust in which the elements are given as oxides, and only the common elements are included, is as follows: —

AVERAGE COMPOSITION OF EARTH'S CRUST.

Oxide.	Symbol.	Per cent.
Silicon oxide (silica) . .	SiO_2	59.87
Aluminum oxide (alumina) .	Al_2O_3	15.02
Ferric oxide	Fe_2O_3	2.58
Ferrous oxide	FeO	3.40
Magnesium oxide (magnesia)	MgO	4.06
Calcium oxide (lime) . .	CaO	4.79
Sodium oxide (soda) . .	Na_2O	3.39
Potassium oxide (potassa) .	K_2O	2.93
Hydrogen oxide (water) . .	H_2O	...
Hygroscopic water † . .	..	.40
Chemically combined water ‡	..	1.46
		97.90

CHEMICAL CHARACTERISTICS OF THE COMMON ELEMENTS.

The fact that these oxides fall into several natural chemical groups is utilized in the classification of the minerals and rocks which they unite to form, and it is therefore important to briefly discuss their relationships and differences. *Silicon* is the only one of the common elements save oxygen which is not a metal,

† *Hygroscopic water*, the rock moisture completely expelled by heating just above the boiling point.

‡ *Chemically combined water*, that entering into molecular composition in the rock minerals, only expelled at temperatures considerably above the boiling point.

and therefore its oxide, silica, is the only *acid radical.* As such it stands in opposition to all the other oxides; and, from its abundance, exceeds in the percentage of its occurrence their entire sum. The other oxides, being those of metals, act chemically as *bases,* so that, in the crystallization of molten rocks, complex salts originate, consisting of combinations of silica with the basic oxides and known as *silicates.* These silicate minerals form several distinct groups, and comprise somewhat more than four-fifths of the primary rocks of the earth's crust from which all other rocks are derived. The chemical bonds between all the elements of the silicates are so close that the oxides are not thought to exist in the combination as individual entities; and in the building up of the mineral molecule oxides as preliminary combinations may not have existed, although in some cases they have done so. The analysis of a rock into oxides is therefore to a considerable extent a device to facilitate the chemical study and classification of rocks, and does not necessarily mean that the several oxides have ever had an individual existence before their combination into the final mineral form.

The primary or fundamental rocks of the crust are called *igneous rocks,* from the fact that they have solidified from fusion. Although it is seen from the table that on the average such rocks contain about 60 per cent. of silica, there is nevertheless a wide variation in individual rock masses. Some dark and heavy rocks such as basalts may have as little as 40 per cent. of silica, and on account of their excess of basic oxides are known as *basic rocks.* Others, such as granites, may possess from 70 to 80 per cent. of silica, and from their excess of the acid oxide are known as *acidic rocks.* The amount of silica is therefore the most fundamental chemical characteristic, and is used as a basis of classification of the igneous rocks.

Silica, when set free from its chemical compounds, shows in its finely divided and nascent state considerable capacity to combine with water and become slightly soluble. This solubility is also increased by the presence of soluble alkalies or high temperatures. Where the pressure becomes very great, as at a depth of a mile or more in the earth, so that water is held in the rock and prevented from turning to vapor even at temperatures far above 100° C., silica and water show a surprising power of inter-

action and solution. Under these conditions silica may be carried in solution, acting as a cementing medium of rocks, or becoming concentrated in fissures, although under surface conditions it is one of the most insoluble of substances.

Carbon, the next most important non-metallic element, forms two oxides; the one, carbon monoxide, CO, resulting when carbon is burned with a deficiency of oxygen, the other, carbon dioxide, CO_2, the most abundant gas resulting from combustion of coal, being the fully oxidized form. At high temperatures carbon dioxide is dissociated from its compounds with metallic oxides, and forms a heavy, colorless gas. It belongs to the same group of elements as silicon; and its oxide, CO_2, shows at ordinary temperatures a power, when dissolved in water, to slowly attack and break up the compounds of silicon. In this manner it sets silica free, and itself uniting with the basic oxides, forms *carbonates.*

Hydrogen, commonly occurring in the form of water, its oxide, is also unable at the high temperature of solidifying rocks to enter into mineral combination except in small quantity, but at ordinary temperatures its oxide tends to combine with other oxides forming *hydrous compounds.* These reversals of chemical relations of carbon dioxide and water between the temperature of solidifying rock and that of the surface of the earth are the fundamental causes of weathering, or rock decay, resulting in the production of soil, when rocks are exposed at the surface, and of certain kinds of metamorphism known as silication, decarbonation, and dehydration, when hydrated and carbonated sediments become deeply buried.

On account of the solubility in water of certain of the hydrous and carbonated products, and the finely disintegrated character of the residue, the soil, the product of rock decay, is continually removed by running water. As it is eroded from above, however, hydration and carbonation renew it from below, and the process of subaërial denudation goes forward, the soil being the temporary form of the rock between the parent formation below and the sediments finally laid down at a distance.

Aluminum and ferric oxides are the next to be considered. It is to be noted that their chemical formulas, Al_2O_3 and Fe_2O_3, are of the same form. Each shows a capacity to occupy the

place of the other in mineral compounds; and both, in the absence of silica or other acid oxides, may play the part of weak acids. Iron in its various forms, but especially in its ferric state, is the only common element of the igneous rocks which possesses the property of giving highly colored minerals. In sedimentary rocks, however, carbon is an equally important source of color. In the presence of water and carbon dioxide, *alumina* and *ferric oxide* form highly insoluble compounds, and are therefore concentrated in the soil upon the decay of the parent rock.

Ferrous, magnesium, and calcium oxides comprise the next group. These are all chemically similar, and are the oxides which commonly predominate in the basic igneous rocks. When acted upon by water to form *hydroxides* or by carbon dioxide to form *carbonates,* they are sparingly soluble in water. In the presence of an excess of carbon dioxide they take up a double amount, forming *bicarbonates,* and as such become more freely soluble.

Ferrous compounds differ sharply from those of magnesium and calcium in their capacity for further oxidation to ferric compounds upon exposure to the free oxygen of the air. And on the other hand ferric compounds are reduced to the ferrous state in the presence of organic matter. As a result, underground waters holding organic acids but no free oxygen dissolve iron in ferrous forms, mainly as ferrous bicarbonate, and carry it until the solution becomes exposed to free oxygen in solution, when it is precipitated as common iron rust, known chemically as ferric hydroxide. In this way most deposits of iron ore have originated, as explained more fully under the subject of the iron minerals.

Calcium and magnesium on the other hand, on account of the solubility of some of their compounds either with or without the presence of oxygen in solution, are found dissolved to some extent in all river waters chiefly as bicarbonates, and in the ocean chiefly combined with sulphur and chlorine as sulphates and chlorides. In the form of hydrates and carbonates they are also found in the soil, calcium in soluble forms constituting one of the elements essential for vegetable growth.

Sodium and potassium, the two remaining ones of the common elements, belong to the group of alkali metals, the most

basic of all metals. Their oxides, soda and potassa, stand consequently at the opposite chemical extreme from the acid radicals. All of the alkali compounds which result from the destruction of the silicates are highly soluble; and, as the sodium compounds are very readily attacked by water and carbon dioxide, the result is that through all geological time sodium has been accumulating in the sea. Potassium salts, on the other hand, have been to a much less extent concentrated in the sea, being held rather tenaciously in the soil, though partly in soluble form. In this condition, they constitute an essential material for the nourishment of land plants.

ASSOCIATION OF THE ELEMENTS.

In the primary or igneous rocks, sodium and potassium tend to be abundant in those which are deficient in iron, magnesium, and calcium, and they are usually associated with abundant silicon. They are therefore present in large amount in igneous rocks of light color and acidic nature, of which granite is a familiar type.

Iron, magnesium, and calcium, having related chemical natures, are found in the igneous rocks in more or less association. Where one is present in fairly large amount, the others also are usually abundant. In such instances the percentage of silicon and alkalies is necessarily relatively low, though the oxide of silicon still comprises about one-half of the rock mass. On account of the presence of the iron, the rocks which are high in these three elements are usually very dark in color. Basalt is the typical rock of this character.

Aluminum shows but indifferent associations with the other elements, and is apt to vary in percentage less than the others.

In conclusion, it is seen that there are four groups of elements, all present in all of the primitive rocks of the earth, but existing in each particular mass in varying proportions. Their unlike chemical natures result in each group giving rise to different classes of compounds upon erosion and rock decay. The chemical characteristics of these common elements are thus the basal cause of their segregation into all the varied rock masses which exist within the crust of the earth, from such deposits as those of pure sand to those of iron ore or salt.

Chapter II.

THE MINERALOGY OF ROCKS.

IGNEOUS, SEDIMENTARY, AND METAMORPHIC (ANAMORPHIC*) ROCKS.

Each kind of mineral is formed under certain definite chemical and physical conditions. The chemical conditions are that the necessary elements must be brought together, and not be under too strong bondage in combination with other elements. The physical conditions are those of temperature and pressure, in which temperature exercises much greater control than pressure. According to the physical conditions which they are under when forming, minerals develop and constitute rocks of three great classes: — the igneous, sedimentary, and metamorphic rocks. It will first be necessary to define these classes of rocks and the conditions under which they originate.

Igneous rocks are those which have solidified from fusion. They are also sometimes known as *primary rocks*, and there has been previous occasion to refer to them. In molten condition the magma has come to rest in its journey toward the surface of the earth, and solidified, either in the form of deep-seated masses only exposed by ages of erosion which have removed the cover rocks, or in the form of dust and lavas poured forth from fissures and volcanic chimneys. In all cases the mineral nature is governed by the high temperatures under which they form.

The Sedimentary rocks are derived at the surface of the earth by rock decay and erosion of earlier rocks. A slight amount of the material forms a mantle of residual earth, but this is con-

* Anamorphism, meaning constructive metamorphism, a term originated by Van Hise, is frequently used in this Bulletin in place of the general term metamorphism, since *metamorphism* in its broad sense properly applies to any *change in a rock mass*, whether the breaking down (*katamorphism*) into the products of rock decay, or the building up (*anamorphism*) of sediments into the complex minerals of schists and gneisses. The term metamorphism as generally used in text-books of geology is hence synonymous with the more specific term anamorphism. In discussions, however, where no doubt can arise as to the meaning, the word metamorphism is used in the sense in which it is used in elementary geologic texts.

tinually being swept away and laid down as sediment, to be buried by later deposits and finally consolidated into rock. Sedimentary rocks cover the greater portions of the land surface, and may have been derived from earlier rocks of sedimentary origin and these in turn from still earlier rocks. Originally, however, such rock materials must have come from the igneous rocks, which constitute the great bulk of the earth's crust, though largely concealed by the overlying sediments. The physical conditions which govern the origin of sedimentary rocks are those of ordinary surface temperatures and comparatively moderate pressures.

The Anamorphic rocks, commonly known simply as the metamorphic rocks, are made from either igneous or sedimentary rocks through their physical surroundings changing to such an extent as to force a change of the character of the rock mass but without breaking down the minerals into simpler forms. The changes in pressure are the most broadly acting causes, and are due chiefly to mountain-making movements which crush the rock and give it new forms. The changes (elevations) in temperature are due either to the proximity of newly intruded igneous masses, or to the deep burial of sediments which brings the lower portions to depths characterized by high temperatures. Anamorphic rocks always become crystalline, but without passing through fusion.

THE NATURE OF MINERALS.

CHEMICAL NATURE.

A mineral may be an element or a compound of elements, and consists of (generally) complex molecules of a definite composition. This composition is given in the tables of minerals as information concerning them, not because the knowledge of it is essential for their determination. Knowing the minerals, however, the chemical composition of the rock becomes in a measure known. For this reason, as well as because the geologic history of the mineral is related to its chemical composition, the formulas for the latter should be learned for all the simpler compounds. In the case of the more complex minerals it is sufficient to know which elements are represented, as it is impossible without analysis to determine their amounts. The variability in the chemical composition of the more complex minerals arises from

two causes. First: it has been pointed out that Al_2O_3 and Fe_2O_3 possess similar chemical properties, and in the complex minerals one oxide may take the place of the other in some of the molecules, the other oxide existing in the remainder of the molecules. Thus the molecular form of the mineral species and consequently its crystallographic nature may remain unchanged or nearly unchanged while the chemical composition is variable. This uncertainty of chemical composition of the molecule is expressed in mineralogy either by employing the sign R and writing the oxide R_2O_3 in which R may be either Al or Fe, or the interchangeable oxide is written $(Al, Fe)_2O_3$. The latter is the method adopted in this Bulletin. Ferrous oxide, lime, and magnesia are similarly interchangeable among themselves in many mineral molecules, as are also potassa and soda between themselves. Consequently in the formulas such forms occur as (Mg, Fe)O, or (Mg, Ca)O, or $(Na, K)_2O$. Second: certain minerals are made up of combinations of two kinds of molecules in indefinite proportions. In the first case it is atoms which are interchangeable, in the second case it is definite *combinations* of atoms which are interchangeable. The plagioclase feldspars (see Table I) offer the best illustration. There are two feldspar molecules which when pure form the minerals albite and anorthite, both being feldspars but with somewhat different form and optical properties. These molecules commonly mix, however, in various proportions, and give rise to crystals intermediate in properties between the two pure types. These gradations can, however, be distinguished only by elaborate methods, so that without chemical or microscopic investigation it is difficult and usually impossible to define the species of feldspar which is present. Where variable proportions of molecules are present in a mineral, as in hornblende, augite, and tourmaline, this is indicated in the tables by the use of x and y before the submolecules, or a complete formula is not given. From these statements it is seen that, while many of the simpler minerals have a definite chemical composition, in the more complex minerals it is only possible to state the presence of certain elements and the absence of others. The probable proportions are given in tables of chemical analyses in the manuals of mineralogy.

PHYSICAL NATURE.

The arrangement of the atoms in the molecule determines the structure of the molecule, and this in turn gives rise to the various physical properties of the mineral. It may be *crystalline,* in which case the molecules are all definitely oriented and related to each other in position, like soldiers in marching order; or the mineral may be *amorphous* (without form), in which case the molecules, while of a definite composition, have no definite orientation, like an unorganized crowd.

If the mineral is crystalline, it may possess a definite form, as a prism of quartz, in case it grew unrestrained by surrounding material; or it may be without a definite external figure on account of having to conform to its surroundings during growth, as illustrated by the quartz grains of a granite. In the latter case the internal structure and orientation of the molecules is the same as in the former, and it should be emphasized that it is upon these properties and not upon the possession of crystal faces that the crystalline nature depends. The cases in which crystals have not been able to assume their external forms are much more common in rocks than those in which the crystals have had a free growth.

In dissolved or molten matter minerals do not exist; and, if solidification is rapid, as in the case of the natural glass *obsidian,* minerals have not been able to form. Such a rock then does not consist of minerals, but of a glass, and from the molecular standpoint is a rigid fluid.

For the sake of clearness it is important that these distinctions which have just been drawn should be held in mind; a rock may consist of glass and not of minerals, or it may consist of amorphous mineral substances (that is, of uncrystalline molecular aggregates of definite composition), or it may be crystalline on a microscopic scale, or the minerals may be visible and determinable by the naked eye. The two latter stages are often referred to as *microcrystalline* and *macrocrystalline* respectively. The last, according to the size of the crystals, may be again subdivided as fine-crystalline or coarse-crystalline. In all the crystalline states the external form is commonly more or less irregular.

THE METHODS OF IDENTIFYING MINERALS.

Where a rock has no minerals, as in the case of a rock-glass, its composition can only be determined by a chemical analysis. Where minerals are present, even if amorphous or microscopic, some indication of the kinds may often be had from the physical properties, especially the optical properties, when studied in thin sections by the microscope. It is only where the minerals are individually visible, however, that much can be done by the elementary student of the subject.

For the identification of the minerals it is essential that the several physical properties be determined and compared with the descriptions of the same. The method of identification therefore is similar to that which a detective employs in the identification of a human individual. In the case of those with whom he is thoroughly familiar, a glance, summing up all of the indefinable peculiarities, is sufficient to identify the individual. In the case of others, however, a series of measurements may be necessary. If the weight agrees with the description within the limits of error, it is possible that the identification may be correct; if the height also is identical, it is probable; while, if the color of hair, eyes, and other characters agree, the probability of correct identification becomes almost certainty. Applying the same logic to the identification of minerals, the beginner should never rest content with a determination by eyesight alone until by repeated experience the mineral in question in its different varieties is familiar beyond the possibility of error. On the contrary, a conscious effort should be made to determine the hardness, cleavage, or any other physical peculiarity, and to see if these are in agreement with the text-book statements in regard to the mineral in question. The eye should also be assisted by the use of a hand lens, as only in this way may small details be definitely and satisfactorily seen. For the purpose of studying rocks a low power is best, as it embraces more of the rock surface and brings different depths into focus at once. A single lens of a cheap grade will do satisfactory work. In using it, it should be held so close to the eye as almost to touch the eyelashes, and the specimen brought up until in focus. This method diminishes the strain on the eye.

THE PHYSICAL PROPERTIES OF MINERALS.

Before describing the characteristics of the common rock-making minerals the physical properties of minerals in general must first be discussed.

HARDNESS.

The hardness of a mineral is measured by the resistance which a smooth surface offers to abrasion. The degree of hardness is determined by observing the comparative ease or difficulty with which one mineral is scratched by another, or by the finger nail, or by the knife or file. To give precision to this physical character a scale of hardness is employed, as follows, those minerals which occur rather abundantly in certain rocks being printed in italics: —

1. *Talc*	6. *Orthoclase*
2. *Gypsum*	7. *Quartz*
3. *Calcite*	8. Topaz
4. Fluorite	9. Corundum
5. Apatite	10. Diamond

The finger nail has a hardness of about 2.5, and the knife blade about 5.5 to 6.2, window glass has a hardness of about 5.5.

Crystalline varieties of minerals with smooth surfaces should be employed for testing hardness, and it should be noted that minerals of grade 2 are easily scratched by the finger nail; those of grade 3 are readily cut with a knife; those of grade 4, scratched rather easily by the knife; grade 5, scratched with some difficulty; grade 6, scratched by quartz but only with considerable difficulty by the knife and not at all by window glass. Minerals of grade 7 will scratch glass readily and also the steel of a knife blade.

Practice with the finger nail and knife blade will lead to a fair approximation of the hardness of all the common minerals, but care must be taken to distinguish the weak adhesion of slightly cemented grains in a mineral aggregate, such, for instance, as semi-consolidated sand, from true softness, which is due to weak cohesion; and also to distinguish brittleness from softness.

CLEAVAGE.

Cleavage is the tendency of a crystallized mineral to break in certain definite directions, yielding more or less smooth surfaces which may be frequently repeated in a parallel series. It obviously indicates a minimum value of cohesion between the layers of molecules in the direction of easy fracture, and it results from the orderly arrangement of the molecules, like hills of corn in a cornfield. The latter illustrates how certain lines may be in imagination drawn through a crystal without intersecting the molecules. In the cornfield there are two directions at right angles, the lines used in cultivation, in which the rows of corn are farthest apart, but in which there is the greatest number of plants in a row. This illustrates the theory that the cleavage planes are those systems of planes on which the molecules are either most closely packed or most strongly bound together, while the successive planes of molecules are relatively far apart or weakly bound, rendering cohesion weaker between the planes and cleavage easy.

Where cleavage is highly perfect in one plane, as in mica, a series of broad lustrous platy surfaces will result from fracture. Where cleavage is equally perfect in two planes, the intersection of these produces fibrous or prismatic structures through the mineral. Where the cleavage is of unequal perfection in two planes, the luster and smoothness of one will be different from that of the other, and upon fracture there is a tendency to develop a step-like structure in which the better cleavage forms the broader surfaces. Where three cleavages occur, there is a tendency for the mineral to break into fragments regularly bounded in three directions according to the perfection of each of the cleavages. Where three equally perfect cleavages exist at right angles, the result is a cubical cleavage, as in galena and rock salt. Where three equally perfect cleavages are oblique to each other, the result is a rhombohedral cleavage, as in calcite.

In testing for cleavage, it should be remembered that cleavage is a *capacity to break* in a certain direction, and has no relation to the external crystalline form except that a cleavage direction is always the direction of a possible crystal face. A mineral may show a highly developed crystalline form, as a quartz prism, and yet possess no appreciable cleavage; while on the other hand

the absence of an external crystalline form may accompany the capacity for perfect cleavage. It is only by breaking such a mineral that the question of cleavage may be settled. Care must also be taken to distinguish between cleavage and mere glassy fracture. This may be done by noting the smoothness and the planeness of the surface, and whether or not it is repeated parallel to itself within the same individual crystal. The question of cleavage in a mineral may often be determined by holding the specimen so that a beam of light strikes it. If in a room use the light from a window, if outside use the light from the sun, and note whether upon turning the specimen a flashing or twinkling occurs due to a reflection when in certain positions. A mere fracture, having a somewhat curved or irregular surface, will not give the same effect. Where more than one cleavage is present, the angle between the two planes may sometimes be determined by the contact goniometer, though more accurate values may be obtained by the more elaborate methods of the mineralogist. The angle between cleavage planes or crystalline faces may often, however, be estimated with fair approximation by holding the line of intersection of the two faces in line with the eye, when the full value of the angle is perceived. If this is impracticable, some idea may be gained by turning the crystal fragment in the light and noting the approximate angle of rotation between the two successive flashes. The angle determined from the mineral may be either the angle as given in the tables or its supplement.

COLOR AND STREAK.

In regard to color, minerals may be divided into two groups; first, those in which the powder is of the same color as the mass, as in many of the iron ores; and, second, those whose powder possesses a different color from the mineral in the mass. To this latter group belong most of the common minerals, embracing especially the silicates. In these the color of the mass is often quite unessential, being often due to the presence of a small amount of some metallic oxide which may be no essential ingredient of the mineral. In the powder, however, such small amounts of impurities have but little color effect, so that the

powder is more constant in color value and frequently important in identifying the mineral species.

The reasons for the contrast in color are found in the fact that in most silicates the pure mineral in the mass is more or less transparent, giving coloring materials an opportunity to show. The powder of a transparent mineral is, however, white, on account of the multitude of reflections from microscopic surfaces; and the color, unless so intense as to show in a microscopic particle, disappears.

The color of the powder is obtained by scratching the surface of the mineral with a knife or file, or, if not too hard, by rubbing it on a surface of unglazed porcelain. The powder left by the scratch is called the *streak,* and the test should always be employed in colored minerals.

OTHER PHYSICAL CHARACTERISTICS.

Other important characteristics are found in the mode of crystallization, in the luster, transparency, optical properties with the microscope, etc. These are essential for the understanding of mineralogy; but for the present purpose, which is to enable the student to distinguish and identify the common rock-making minerals, they may be omitted from consideration.

DESCRIPTION OF MINERALS.

INTRODUCTION.

In the discussion of the chemical relations of the elements, it was seen that most compounds which had been formed at high temperatures were not stable at lower temperatures in the presence of water and carbon dioxide. This chemical contrast gives rise to two distinct chemical zones in the earth's crust, the one situated some miles beneath the surface, characterized by high temperatures and great pressures, resulting in the formation of complex silicates and anhydrous minerals of great density. Under these conditions are formed the minerals of the igneous and metamorphic rocks. Where molten rocks are brought to the surface, temperature conditions natural to a greater depth exist during the solidification. Minerals are formed which are stable under conditions where these high temperatures are

permanent, but which are unstable at surface temperatures when in the presence of water and carbon dioxide and to a more limited extent in the presence of oxygen. Therefore, as soon as the rock cools it begins to suffer destruction in so far as these substances can permeate the rock and attack its minerals. These minerals consequently belong to a deeper zone, although formed at a higher level. The other zone, situated at and near the surface of the earth, is marked by the presence of moderate temperatures and pressures. In this zone the silicate minerals are, as just stated, broken up; destructive metamorphism, known technically as katamorphism and popularly as rock decay, takes place, and the materials are derived for the forming of the sedimentary rocks. These relations allow the common rock-making minerals to be classified into three groups as shown in the tables at the end of Part I. A brief supplemental description should be sufficient to identify them, but the study of the tables and descriptions is of little value unless accompanied by specimens of the minerals as they occur in rocks. For this purpose, as noted in the introduction, if the student knows of no one to point out specimens of them, it is of great advantage to purchase a small student collection of minerals.

COMMON MINERALS OF IGNEOUS AND ANAMORPHIC ROCKS.

Ratio of Occurrence.

Clarke has given the average mineral composition of the igneous rocks as follows: —

Quartz	12.0
Feldspars	59.5
Biotite	3.8
Hornblende and Augite	16.8
	92.1

The list indicates the great dominance of a few minerals in this group of rocks which constitutes the bulk of the earth's crust. These minerals are also dominant in metamorphic rocks, made by recrystallization without fusion, but in different proportions; and in the latter group the occurrence in many localities

of other minerals in a conspicuous manner requires the addition of a special table.

Notes Supplemental to Table I.

Quartz. — Quartz is a mineral of extremely simple composition, consisting of the oxide of silicon. The existence of silica in a free form in the igneous and metamorphic rocks is owing to the great abundance of this oxide in the crust and its occurrence at many places in much more than the average amount, so that even when combined in the maximum proportion possible with the other oxides there is still an excess of free silica in the rock. Quartz occurs in a great variety of forms, but is usually determined readily. It occurs with its external crystalline symmetry where it has developed in open cavities surrounded only by gases or fluids at the time of its growth. This crystal form is characterized by a six-sided pyramid, with smooth sides and glassy luster, capping a six-sided prism whose sides are very commonly horizontally striated. The crystal when broken shows an irregular glassy fracture and an absence of cleavage, offering a good example of the distinction between crystalline form and cleavage.

The usual mode of occurrence of this mineral in the igneous rocks is as irregular grains filling the spaces left by the crystallization of the other minerals. In the weathering of the rock mass these grains, being themselves not subject to decay, are set free. In the subsequent transportation by currents they are rounded and smoothed by their mutual friction, and separated at least to some degree from both the finer and coarser grains, which consist respectively of softer and harder materials. In this way quartz sand deposits arise, which upon subsequent burial are converted into sandstones.

The massive veins of quartz filling fissures in many rocks, yield, upon the decay of the surrounding rock, pebbles and cobbles, whose segregation gives rise to quartz gravels. These quartz fillings most commonly consist of white or milky quartz but are sometimes of various tints. The fractured surface of the resultant pebbles is rough in a broad way, but curved and glassy over small areas.

A third variety of quartz is that classified in Table II,

Minerals resulting from Rock Decay, as cement quartz, and results largely from the destruction of silicates, especially from aluminous silicates, since clay, the form into which the alumina goes upon the destruction of aluminous minerals, has less silica in combination than most of the minerals from which it comes. In part cement quartz may be derived from the solution of ordinary quartz when in the presence of hot or alkaline waters. Such silica seldom forms crystals except on a microscopic scale, and may be of other crystalline structure than that of ordinary quartz. The aggregate may be massive as in *jasper, carnelian,* and *flint,* or form as an incrustation of differently colored layers as in *agate* and *onyx.* When the incrustation shows a somewhat fibrous fracture at right angles to the surface it is called *chalcedony,* and, if finely crystalline with a surface of velvety luster, it is called *drusy quartz.* Silica also occurs combined with water as *opal,* forming incrustations of waxy, greasy, or opalescent luster which are somewhat softer than quartz. Where cement quartz occurs filling up the pore spaces of rocks, the cementing material is added in crystalline continuity to the quartz grains, extending their limits and dovetailing them together. In this way porous *sandstones* are turned by metamorphism into compact *quartzites,* characterized by their lack of porosity and a rather smooth but slightly flaky and faintly granular fracture. The general appearance of a broken surface is somewhat like that of a cake of maple sugar.

Feldspars. — The feldspars occur as a distinct and easily recognized family of minerals, which grade into each other, and which often can be distinguished from each other only by means of a chemical analysis or the study of thin sections with the compound microscope. On account of the great abundance of the feldspars in all crystalline rocks, however, as well as from the fact that many systems of rock classification have been based upon the occurrence of the different kinds, it will be necessary to briefly discuss them. It should be said in advance, however, that any system of classification which requires the determination of the kind of feldspar present in a rock can be used only by the professional petrographer, and is not adapted for the ordinary study of rocks.

The complexity of the feldspars is due, as discussed briefly

under the chemical nature of minerals on p. 29, to the existence in some of them of two forms of molecules, as shown in the table. The one is the *alkali molecule,* containing either potassa or soda and high in silica, containing from 64.7 to 68.7 per cent. of the latter oxide. The other, the *lime molecule,* is comparatively low in silica, containing but 43.2 per cent.

The alkali molecule occurs in many rocks free from admixture with the lime molecule. In that case it most commonly contains potassa, giving the *potash feldspar, orthoclase,* though more or less of the soda molecule may be intermixed. Orthoclase is much more resistant to decay than the other feldspars, and its freshness is indicated in a specimen by the possession of cleavage faces with high luster. When weathered, the mineral becomes chalky, loses its luster, and gives a clayey odor. Feldspar is rarely transparent, but is usually white and opaque, owing to the multitude of microscopic reflection surfaces within it. When iron oxide is present as a foreign coloring substance, the orthoclase may be pink, or more rarely green. Where part of the feldspar of a rock is less weathered and of a lighter or pinker tint than the other part, it may be regarded with some confidence as orthoclase.

The lime molecule occurs rarely in a pure state, forming the mineral *anorthite,* but is usually mixed with various amounts of the soda molecule, which when occurring alone is called *albite.* The feldspars resulting from the intermixture of the two, as well as the pure anorthite and albite, are called *plagioclase,* and are subdivided into several species according to the ratio to each other of the soda and lime molecules.

In the table the indefinite ratio of the two molecules is expressed by giving as the composition of plagioclase x molecules of the soda feldspar plus y molecules of the lime feldspar. In the same crystal the ratio is apt to vary from center to circumference, with the result that certain shells weather more readily than others. Where the crystals are large this may give rise to a perceptible *zonal structure.* If the crystals are well developed, they may be distinguished from those of orthoclase feldspar by the angle between the cleavage faces, which is slightly greater or less than a right angle. In this case the crystal is usually made up of a series of thin laminæ parallel

to the less perfect of the two well-marked cleavage planes. These laminæ are alternately turned around with respect to each other like a row of books in which every other one has its back turned to the wall. The result is that on the most perfect cleavage surface a series of striations appear, giving a minutely ruled or ribbed effect. The detection of this feature may require the use of a hand lens, and in certain cases it is developed on a microscopic scale.

As previously noted, the alkalies are apt to occur in large quantity in those rocks high in silica and low in lime, iron, and magnesia. Since iron gives strong colors to its compounds, it results that the alkali feldspars are especially associated with the light colored rocks, and are the typical feldspars of granites. On the other hand, soda-lime feldspars are apt to be associated with lime-iron-magnesia minerals, and therefore are more characteristic of crystalline rocks possessing a notable quantity of dark minerals. These rules of occurrence, however, are by no means universal.

In absolutely fresh feldspar, which has not been subjected to earth strains, there may be considerable superficial resemblance in a fine-grained rock to a rock composed of grains of quartz. Usually, however, the feldspar is readily distinguished by its opaqueness as well as by its cleavage.

In the fine-grained rocks the feldspar may be granular or in the form of minute rods. In the coarser rocks it shows a tendency to assume polygonal and especially rectangular outlines, hindered in development to some extent by mutual interference.

On considering the great dominance of feldspar in the igneous rocks, amounting to approximately 60 per cent., and considering further that all the materials of the sedimentary and metamorphic rocks have been made from the igneous rocks, it is seen that to the decay of feldspars through all geological time must be attributed the bulk of the salt in the sea, as well as the potash and the clay of the soil and of those rocks which are the solidified muds of earlier geological ages.

Micas. — The micas form a group of aluminous silicates, consisting of many species which, as shown by the two listed in the table, have a fairly complex composition. They contain generally

from 4 to 5 per cent. of water, which, being an essential part of the mineral, known as "water of constitution," is only driven off on heating the mineral to redness. They also contain some alkali metal, by far the most common being potassium, and various amounts of magnesium and iron. Several of the species can only be determined upon detailed investigation, and for elementary purposes in studying rocks only the two common ones need be considered.

All of the micas are characterized by the perfection of the single cleavage, allowing the mineral to be split into thin elastic sheets or flakes possessing highly lustrous surfaces. They are of about the same hardness as the finger-nail, so that the cleavage surfaces may be sometimes scratched by it. When the crystals are of some size and more or less freely crystallized, they form rather rough-sided hexagonal prisms commonly shorter than broad. The cleavage surface is parallel to the ends of the prisms. In the rock masses the flakes of mica occur of all sizes, from large and commercially valuable sheets several inches in diameter, to aggregates of microscopic scales which in the mass serve to give a smooth and lustrous but irregular cleavage surface to some schists. Commonly, however, the individual flakes may be distinguished by the eye.

Muscovite, the first species to be considered, is common in rocks which are free from iron, and therefore is often found in schists, frequently in granites. When seen in large crystals or in aggregates of small ones, the color may be brown, pale green, or some other light color, but thin flakes or plates are transparent and colorless.

Biotite differs in chemical composition from muscovite in the possession of iron and magnesium, and this is expressed by the difference in color as well as by other but less obvious physical distinctions. Even in the thinnest laminæ the color is deep green or dark brown. The crystals of usual size are black, sometimes with shades of green or brown. Biotite often occurs associated with some other black mineral, more especially with hornblende.

Hornblende and Augite.—Hornblende is the common representative in the igneous and metamorphic rocks of a group of minerals known as the *Amphiboles,* and Augite is similarly the

common representative of the group of *Pyroxenes*. The two groups are allied but differ somewhat in molecular composition, and this is expressed in a different form of the prism. Within each group the members are characterized by the various amounts of alumina present and the degree to which lime, iron, magnesia, and more rarely the alkalies, replace each other. The composition is thus variable, but the limits of the possible variations are sharply fixed, and the relations of the atoms in the molecule and consequently the structure and form of the molecule must be nearly constant. This uniformity of molecular structure expresses itself in the similarity in crystallization within a group, giving the characteristic features to each and serving to distinguish them from each other. The two groups together constitute about 17 per cent. of the igneous rocks; but except by the specialist with adequate apparatus are usually difficult to distinguish, and they are hence treated together. The common forms are black, but are readily distinguished from biotite by their superior hardness and brittleness, by the prismatic instead of the tabular cleavage, and usually by a duller luster. The crystals as they occur in the rocks are often developed on a small scale, so that the aggregate may appear somewhat fibrous or like a mass of minute sticks. When they occur matted together a somewhat velvety effect may be produced.

Hornblende is characterized by two good cleavage planes parallel to the sides of the prism and making angles of 56 and 124 degrees with each other. The intersections of these planes, when they have been developed throughout the mineral by earth pressures, result in a fibrous structure within the individual mineral, and, when the end of the crystal is viewed, are seen to give a diamond-shaped pattern of intersecting lines. When the ends of the crystal are finished with crystal faces, the latter are seen to make angles of 74 degrees with the axis of the prism, the ends of the crystals thus being oblique.

Augite differs from hornblende in usually carrying more lime in its composition, and in the somewhat different crystallization. The sides of the prism make angles of 87 and 93 degrees with each other; and neither the luster, the prismatic form, nor the cleavage is usually so well developed as in hornblende. The crystals are often chunky, tabular, or granular. They are best

distinguished from hornblende, however, when the prismatic form or the cleavage planes are developed to a degree allowing the included angle to be observed. A lens is of course usually necessary to observe this distinction.

The associations of the three black minerals, biotite, hornblende, and augite, with other minerals are fairly characteristic, although exceptions are to be found. In the presence of quartz, biotite is the most common in occurrence and hornblende next. The association of quartz and augite is rare. Biotite and hornblende are often associated in the same specimen, and also hornblende and augite. Biotite and augite may occur together, but the association is not so common. Augite is the least stable when subjected to crushing or to the action of interstitial water, and biotite the most so, with the result that augite is apt to occur in basic igneous rocks only when fresh. In metamorphism, where pressure is the chief agent involved, augite is apt to recrystallize as hornblende.

Olivine. — Olivine is not a common mineral in comparison with the others, and when present is usually in grains too small to be readily detected by the unassisted eye. Nevertheless from its chemical significance it is useful in classifying the basic igneous rocks — those which, as before mentioned, are characterized by a dominance of iron, magnesia, and lime. Hornblende and augite commonly possess from 45 to 50 per cent. of silica, while olivine carries from 38 to 40 per cent. Therefore, when silica is low in the rock mass, olivine forms to some extent during the crystallization along with the hornblende or augite, the proportion of the two being determined largely by the amount of silica present. Olivine is made of a mixture of two molecules, Mg_2SiO_4 and Fe_2SiO_4, respectively. The first is always present in excess, but since the proportion is indefinite the formula is written in the table as $(Mg, Fe)_2SiO_4$. The mineral occurs in the igneous rocks as glassy grains somewhat resembling quartz. The two minerals never occur together, however, since the presence of quartz implies an excess of silica, the presence of olivine a deficiency. Olivine therefore is generally associated with a considerable amount of the black minerals and plagioclase feldspar. It is further characterized by its clear yellowish-green color, the possession of a fair but not good

cleavage, and the ease of its decay; so that its preservation is not to be expected in any rock which shows a notable degree of weathering.

Magnetite. — Magnetite in small or even microscopic grains is present in sparing amounts in almost all igneous rocks. It is apt to be associated with biotite or some other mineral containing iron, and, in such cases, it may occur in highly siliceous rocks. Where it exists scattered through the rock in notable amount, however, it indicates a deficiency of silica, since, save pyrite, which occurs in still smaller amounts, it is the only one of the common rock-making minerals of igneous rocks which carries none of that oxide in its composition. It stands therefore at one end of the list of minerals, as the only free metallic oxide, silica standing at the other end of the list, and the silicate minerals between. The presence of magnetite is readily recognized by crushing the rock to the fineness necessary to liberate the magnetite and then drawing a magnet through the powder; or, if the magnetite is present in considerable amount, its magnetic action allows its presence to be readily determined without crushing the rock.

Pyrite. — In igneous rocks sulphur exists in small amounts, combined with iron or with some of the rarer but valuable metals such as copper, nickel, zinc, etc. By far the commonest form of occurrence is as iron sulphide forming the mineral pyrite, called sometimes "fool's gold" from its resemblance to gold in color and luster, though differing in all other respects. Pyrite is readily identifiable from its striking color, its hardness exceeding that of feldspar, and its occurrence as scattered crystals, usually cubical in form, though sometimes developed with twelve pentagonal faces. It also occurs in radiating clustered needles, and in massive globular forms. These imperfectly crystalline forms of iron sulphide, however, are often *marcasite*, a mineral identical with pyrite in chemical constitution, but differing in crystalline structure.

In the original igneous rocks pyrite usually occurs in small scattered crystals, associated with magnetite grains and biotite flakes, and is seldom noticed. The more conspicuous occurrences are those where it has been concentrated into more abundant and larger crystals by means of underground waters, either by

emanations of water vapor from a previously intruded and still hot igneous mass, or by the deep-seated circulation of rain waters. Consequently, it is especially characteristic of veins and impregnations in the walls of fissures rather than of the unaltered igneous mass. It also occurs abundantly in association with carbonaceous strata in sedimentary rocks, giving rise to the objectionable presence of sulphur in coal.

Pyrite possesses less power of resistance to surface weathering than any other common mineral, both the iron and sulphur being readily oxidized by the presence of atmospheric oxygen in water solution. Rocks which have pyrite scattered through them in abundance consequently crumble and slake upon a few years' exposure to the weather, and those rocks with scattered crystals become blotched with brown stains of iron rust, hydrous iron oxide.

MINERALS RESULTING FROM ROCK DECAY (KATAMORPHISM).

Relations of Minerals to Rock Decay.

Katamorphism, signifying *destructive change,* embraces those activities of water, carbon dioxide, and oxygen which operate under conditions of moderate temperature and pressure, and result in breaking up the complex silicates into simpler mineral compounds. It is *destructive metamorphism* leading ultimately to that disintegration of rocks known as rock decay or weathering.

Quartz and *magnetite,* the uncombined acid and basic oxides, respectively, and the simplest in constitution of the igneous minerals, are the only ones which effectively resist the action of water and carbon dioxide at the surface of the earth, and which therefore pass over substantially unaltered into the derivatives of the igneous rocks, the sedimentary rocks.

Quartz grains set free by the decay of the parent rock suffer to an appreciable extent, however, through mutual abrasion during transportation and through slight solution, but the volume of the quartz grains is supplemented by the *cement quartz* set free by the decomposition of the alkali feldspars. The characteristics of quartz, having already been fully considered, require no further discussion at this place.

Magnetite also suffers somewhat from abrasion and from the action of organic acids and oxygen. From its high specific gravity it is transported with difficulty. From this cause and the fact of its originally small percentage in the average igneous rocks it is a negligible factor in those of sedimentary origin.

Kaolinite. — The minerals resulting from the breaking up of the silicates are characterized by their softness and usually uncrystalline state. Transitional between the original silicates and their final and simple decomposition products stand a number of intermediate forms, the hydrous silicates — minerals in which water has been absorbed but the silica not yet lost. The first of these listed in the table, kaolinite, the characteristic ingredient of clay, suffers no further decomposition, the silica and alumina being bound to each other by bonds of chemical affinity so strong that no process is known for economically separating the valuable metal aluminum from this combination.

The *chlorites* and *serpentine,* however, as well as other related minerals which are less abundant, are merely transition products which become destroyed upon complete decay. *Talc,* so far as known, does not suffer further chemical alteration while in the rocks, but disappears during the process of erosion.

It will be noted that in complete decomposition each element tends to come to rest in one particular mineral form, but occasionally somewhat different chemical or physical surroundings result in some other form.

Climate and Topography as Factors in Rock Decay.

Although carbon dioxide and oxygen are active agents in destroying the minerals of the igneous rocks, their activity is conditioned upon the presence of moisture. This is illustrated by the familiar facts regarding the rusting of iron or the decay of wood. Chemical destruction known as rock decay therefore is nearly absent in the more arid regions of the world. Nevertheless, it is observed that erosion in such regions goes forward, the rocks being gradually broken down by the expansion and contraction due to the rapid changes of temperature occurring between day and night, as well as from the impact of sand grains driven by the wind. The potency of these forces working ceaselessly over broad areas is witnessed by the shattered

bowlders which strew many desert surfaces and the etched character of rock masses exposed to the natural sand blasts. The rush of waters in the cloudbursts which occasionally visit nearly all deserts is also an important factor in baring anew the rock surfaces and cutting precipitous valleys.

In high mountain regions and in high latitudes also, as well as in deserts, the forces of rock decomposition are weakened. On account of the low temperatures prevailing the chemical agencies either act more slowly or, on account of the water being frozen, act not at all.

In addition to the disintegration produced by the great changes of temperature which occur in such regions, the great power of frost is to be noted; water freezing in the joint planes, and upon every refreezing heaving the joints wider open. Rocky cliffs may by this means be transformed into talus slopes with great rapidity as measured by the scale of geological time. In mountain regions the streams furthermore quickly remove this débris and expose the rocks to further disintegration. In all of the more desolate parts of the earth, therefore, whether due to great heat and dryness, to rugged slopes, or to arctic cold, mechanical weathering is in excess over weathering by chemical agencies.

A sandstone made largely of feldspar fragments is consequently seen to contain a record of an ancient climate and topography very different from a sandstone made of quartz grains and cemented by a true clay.

In conclusion, erosion is carried forward by two distinct processes, — *rock decomposition,* operating dominantly where chemical forces are more potent than mechanical forces; and *rock disintegration,* where the reverse relation holds true. These are both manifestations of weathering, but should be as carefully distinguished in thought as they are in nature. Under the present topic, "minerals resulting from rock decay," it is only with the former that we have to deal.

Notes Supplemental to Table II.

Kaolinite, commonly called kaolin or clay, is the most abundant mineral resulting from rock decay, but seldom occurs

in pure form. It originates as a chemical residuum from the solution of the soluble portions of the aluminous minerals; and, unless the leaching waters are deoxidizing, whatever iron is present in iron-bearing minerals is also left behind as the insoluble hydrous oxide, limonite, coloring the clay yellow. If the iron be removed, it is usually by water carrying organic acids derived from decaying vegetation. In this case the residual carbon from the organic matter ordinarily colors the clay gray or black. Iron oxide and carbon are thus common impurities and coloring matters in deposits of clay. The clays impure with iron oxide burn to a red color, those carrying carbon and without iron burn to a white, and are hence more valuable. Another common impurity of clay is finely comminuted quartz, which can usually be detected by rubbing between the fingers. If so fine that this test fails, the quartz may still give a perceptible grit to the teeth. Clay soaks up water slowly, but transmits it only with great difficulty, and hence may hold appreciable amounts of such minerals as calcite, or potassium minerals of hydrous and gelatinous forms. Such impurities can usually be detected only by chemical means. It is to this power of holding partly decomposed and soluble ingredients and giving them up but slowly to percolating waters that clay owes its agricultural value as a principal ingredient of soils. Clay is unique among common rock materials in its plasticity when wet. When partly dry it may be detected even when present in insignificant amount by its odor. If absolutely dry, the specimen may be moistened by the breath and then tested for odor before the moisture has evaporated.

Upon consolidation of clayey sediments into rock, the clay loses a portion of its water of combination, passes into other mineralogical forms, and loses its characteristic odor. Reweathering, however, by restoring the water, turns the aluminous material once more into kaolin.

Chlorites. — The chlorite group includes many species of which only a few are distinctly crystallized. The others occur more or less intermixed and in scales or fibres, or in earthy forms, and their composition is more or less undetermined. They are all closely allied, however, and characterized by the green color from which they take the name of chlorite. For these

reasons no effort is made in lithology to separate them, and any example is referred to as a chlorite. The formula put down in the table is therefore merely a typical one representative of the group. They are all silicates of aluminum with ferrous iron and magnesium and chemically combined water. They differ from the micas, to which they are crystallographically allied, in the absence of alkalies. The chlorites originate from the alteration of any of the ferromagnesian silicates, such as biotite, hornblende, or augite; and the form of the original mineral may still be evident, the chlorite either taking its place or existing diffused as a green stain through the surrounding material.

Serpentine and Talc. — These two minerals are both hydrous magnesian silicates, and are closely related to each other, differing chemically in the proportions of magnesia, silica, and water; and differing from the chlorites, to which they are nearly allied, by the absence of ferrous oxide and alumina as essential constituents.

Serpentine is ordinarily found in massive forms and more or less impure, especially from iron oxide. When massive and translucent, it is of a honey-yellow to light oil-green color, with a waxy or resin-like luster; but common serpentine, owing to the impurities, is less translucent, is of darker shades, sometimes almost black, and may have a hardness as high as four. Delicately fibrous forms known more specifically as chrysotile often occur, the fibers usually flexible and easily separating. On account of the internal reflections the color is generally lighter than in other varieties, and may be snowy white. The fibrous portions often constitute seams in massive serpentine, and are the source of a large part of commercial asbestus. Serpentine is often observed as a fine mesh enclosing granules of still unaltered minerals, especially olivine; and it frequently occurs with calcite or dolomite, forming greenish, clouded marbles. These two modes of occurrence point to its double origin; from the leaching and hydration of basic magnesian igneous rocks, and from magnesian and siliceous limestones.

Talc, the softest of all common minerals, occurs abundantly in several forms as an alteration product in rocks containing much magnesia. The most common mode of occurrence is as scaly aggregates, the scales resembling the micas in appearance

but much softer, with flexible but not elastic laminæ, and giving a greasy feel to the hand. The usual color of talc is an apple-green with variations toward white. It may occur, however, as a massive white or gray rock known as soapstone. Where resulting from the alteration of a fibrous mineral, it may keep the fibrous form.

The three minerals, *chlorite, serpentine,* and *talc,* may occur more or less intermixed; but, when any one of the three is present in notable amount, it may be distinguished from the others by certain characteristics. Chlorite is of a more intense green, is but little softer than the micas, and is most likely to occur in crystalline form. Serpentine has shades of yellow in the greenish color, is apt to be harder and blacker when massive, and often occurs in fibrous form. It never shows a truly crystalline form. Talc is very soft, being easily scratched by the finger-nail, is of a lighter green color, and is very apt to occur in flaky forms with high luster.

Calcite. — Calcium carbonate is one of the common minerals of the sedimentary rocks, being the stable form into which calcium tends to pass under the conditions existing at the earth's surface. It may occur uncrystalline, as an aggregate of the shells of animals or the limestone mud made from their disintegration; or it may occur crystalline on a microscopic scale, as in the ordinary limestones which are the solidified calcareous muds of previous ages; or it may occur more or less coarsely and visibly crystalline, as in marbles and vein-stones. There are different forms in which it crystallizes, as *calcite* and as *aragonite,* but the former is so much the more abundant that aragonite may be dismissed without discussion.

The best test for the presence of calcite is the application of a drop of any mineral acid, hydrochloric one-half strength being most commonly used, as it does not affect the skin. This acid, by appropriating the lime, sets the carbonic acid free. Only a limited amount of the latter can remain in the water solution, and the remainder is liberated as carbon dioxide gas, resulting in a conspicuous effervescence immediately following the application of the acid.

Further confirmatory evidences of the presence of calcite are found in the hardness (uncrystalline forms being of course gen-

erally less hard but sometimes harder than the well crystallized varieties), and in the cleavage, which is developed with equal perfection in three planes making angles of 75 degrees with each other. The color of calcite is most commonly white, but, as seen in ornamental marbles, a calcite rock, owing to impurities, may be of almost any color.

Calcium carbonate originates through carbon dioxide being carried into the rocks in water solution, the gas being either absorbed by rain from the atmosphere, dissolved from decaying organic matter, or originating as a gaseous emanation from igneous activity. The affinity of carbon dioxide for the metallic oxides of the rocks is so great that only a trace, .04 per cent., exists in the atmosphere, supplied by volcanic emanations and organic decay and probably from other sources as fast as it is washed out by the rain. The carbonates of the alkalies are highly soluble, and so do not remain in the rocks but exist in solution; while those of lime, magnesium, and iron, being only slightly soluble as simple carbonates and but moderately soluble as bicarbonates, exist in solution only in small amount. Of these the carbonate of calcium is by far the most common, being present in solution mostly as bicarbonate in all flowing waters, and finally passing to the sea. In this ultimate reservoir the lime exists in solution chiefly as the sulphate on account of the presence of sufficient sulphuric acid and its greater affinity for the lime. This state is only temporary, however, since the life of the sea draws heavily upon the lime for the formation of skeletons, retransforms it, and builds it up in shells, corals, etc., as solid carbonate. In this form, upon the death of the animals, it is deposited upon the sea bottom. In geologic ages as early as the Cambrian and earlier, it is quite probable that the marine life did not draw as heavily upon the lime as in later ages, and under such conditions it may have been precipitated chemically as well as organically in the form of carbonate.

Although the accumulations of calcite are thus, first, to a limited extent, an interstitial cement resulting from the alteration of rocks, and, second, to a greater extent, an organic deposit upon the sea bottom; various forms of calcite are made upon the land by temporary solution and redeposition, particularly in limestones. The incrustations occurring in caves and calcareous

springs, and calcareous concretions in argillaceous formations, are examples. These, therefore, do not represent the origin of limestone formations but merely the reworking of deposits already made.

Dolomite. — Dolomite consists of a complex molecule, a double carbonate of lime and magnesium, and is the common form in which magnesium carbonate occurs. The ratio of the two carbonates may vary, however, and occasionally pure magnesium carbonate, known as *magnesite,* occurs. As shown by the table, dolomite may be distinguished from calcite by its greater hardness and by the difficulty of its effervescence. In rocks which are made up partly of dolomite and partly of calcite, a further distinction may be observed in weathered portions, since the dolomite is less soluble than the calcite. In a fossiliferous dolomitic limestone the fossils are apt to be of calcite, the matrix of dolomite. In this case the fossils may show as cavities. In employing this criterion of partial solution care must be taken, however, to distinguish a porous structure made by partial solution from an originally loose and porous aggregate.

Dolomite is usually deposited by solutions of magnesium salts coming into the presence of previously formed calcium carbonate. This takes place to a variable extent in the calcareous muds of the sea bottom, since the marine organisms use calcium carbonate almost exclusively, with the result that a large excess of magnesium salts exists in the sea water. A second important origin of dolomite is beneath the land surface. Underground waters carrying magnesium carbonate in solution and passing through limestone strata exchange the magnesium for calcium, which in the form of bicarbonate is more soluble than the magnesium salt, resulting in the process called dolomitization. As dolomite is a denser mineral, this results in a broken and cavernous structure, which has frequently prepared the way for deposits of lead and zinc sulphides.

Gypsum. — Gypsum, as shown by the table, consists of one molecule of calcium sulphate combined with two molecules of water, the latter forming 21 per cent. by weight of the mineral. It may occur in earthy or fibrous forms or in large crystals. In the latter case a highly perfect cleavage is to be noted by means of which the mineral may be split into thin lustrous leaves.

These cleavage surfaces may be distinguished from mica by the fact that their boundaries are diamond-shaped, due to two poorer cleavages intersecting the best cleavage, instead of showing an irregular, or, if belonging to a perfect crystal, an hexagonal outline. The angles between the two poorer cleavages are 66° and 114°. Moreover, cleavage laminæ lack the elasticity which characterizes those of mica. The mineral when in the massive form may be distinguished from talc by its greater harshness to the hand.

Gypsum occurs chiefly as an evaporation product from the waters of inland salt lakes or from marine lagoons. As a result it is associated with deposits of clay, or calcite, or common salt. Where it occurs, therefore, in sedimentary rocks, it is an indication that at the time and place of its origin there existed an arid or sub-arid climate; since only by seasons of dryness and an excess of evaporation over rainfall could the mineral be precipitated. To a minor extent, however, gypsum may occur in the rocks as the result of various chemical reactions not connected with arid climates.

By heating gypsum to a temperature of not over 260° C., half of the water of combination is driven off, and the substance is transformed to plaster of Paris, of great use in the arts on account of its power of reabsorbing water and rapidly crystallizing or "setting" into a solid. Upon being buried by later accumulations to considerable depth in the earth, and thereby subjected to moderate heat and great pressure, all the water is expelled from gypsum, and it is transformed to *anhydrite,* a mineral with the same hardness as dolomite, 3 to 3.5. Anhydrite may be readily distinguished from the carbonates, however, by its lack of effervescence with acids. When crystalline, anhydrite possesses three cleavage planes at right angles to each other, which may be distinguished from a true cubical cleavage by the fact that the three cleavages are all of different degrees of perfection, one of them being highly perfect, the second fairly perfect, but the third only fair. By later erosion of the overlying rock anhydrite may become exposed at the surface of the earth, and under those conditions it tends to weather back into gypsum through the absorption of water.

Iron Ores. — Siderite, ferrous carbonate, is the first to be

considered. It may be distinguished from the carbonates of lime and magnesium by its color and specific gravity. As it readily oxidizes to the ferric state and loses its carbonic acid on exposure to water holding oxygen in solution, it is frequently associated with the result of its oxidation, hydrous ferric oxide, *limonite,* giving a further distinctive characteristic. Within recent years it has been shown that the reaction is largely carried on by oxidizing bacteria which are unable to exist except in the presence of carbonates of iron or manganese.

As has been shown in a previous discussion, iron in the partially oxidized form, FeO, known as ferrous iron, behaves similarly to lime and magnesia, and the ferrous bicarbonate is sparingly soluble in underground waters. Iron is reduced from its normal and insoluble state of ferric oxide (Fe_2O_3) to the ferrous oxide (FeO) by the presence in solution of any substance possessing a greater affinity than it for its excess of oxygen. The products of organic decay, when originating under water and thus without opportunity for free oxidation by the air, are capable of abstracting one-third of the oxygen from ferric oxide, and thus it is especially in the presence of swamp waters that ferrous carbonate is formed. Chemical principles which bear further upon the accumulation of iron are found in the fact that the solubility of ferrous carbonate is diminished, as is that of the other carbonates, by the decrease in pressure which the solution experiences on coming to the surface of the earth. This is because of a partial loss of the dissolved CO_2 to the atmosphere, an excess of CO_2 in solution promoting the solution of the carbonates as bicarbonates. Further, the solubility of ferrous carbonate or bicarbonate is less than that of calcium and magnesium carbonates or bicarbonates.

Bearing these principles in mind, we see that iron ore deposits are made as follows, there being three steps: solution, transportation, and deposition.

The disseminated ferrous and ferric iron are taken into solution, the latter only in the presence of organic matter sufficient to reduce it to the ferrous form. In such solution it is carried underground, protected from the air. Finally it is precipitated by mixing with oxidizing waters or those laden with other suitable substances in solution, such, for instance, as calcium bi-

carbonate. Or upon coming to the surface the pressure is diminished, the excess of CO_2 escapes, and the oxidizing bacteria are able to perform their work. The loss of CO_2 tends to precipitate the iron as $FeCO_3$, but the activity of the bacteria usually causes the precipitation to be in the form of hydrous oxide, *limonite,* accumulating as bog iron ore. The *limonite,* if buried with organic matter, as frequently happens in swamps, is finally again reduced to the form of impure ferrous carbonate, the *siderite* which in the form of clay ironstone accompanies coal beds. By the continued accumulation of overlying material it is protected from either solution or oxidation until there is a reversal of geological activities and erosion takes place of sedimentation.

Limonite, if buried without the presence of sufficient organic matter, suffers no deoxidation. In this case, however, the moderate heat and great pressures which exist at depths of a few hundred or thousand feet in the earth expel the water of combination, which limonite holds rather loosely, and lead to the recrystallization of the hydrous oxide into the anhydrous and denser form, *hematite.* There are various intermediate stages in this process, so that products may be found grading all the way from limonite to hematite. The streak becomes closely similar to that of hematite before all of the water has been expelled.

The larger and purer masses of limonite constitute a limited supply of the iron ores, but such as are used for ores are seldom made directly by surface precipitation, since this form is usually too impure. The available limonite ores on the contrary are those made by the alteration of pyrite to limonite by downward percolating waters carrying oxygen; or by the replacement of calcium and magnesium carbonate rocks by ferrous carbonate, carried downward in solution from the surface. In this latter instance the iron which was originally diffused and unavailable has been concentrated during the progressive erosion of the surface into an underground deposit which may be of great purity. The carbonate thus made by replacement is usually converted through percolation of atmospheric oxygen to limonite, and may be further transformed into hematite. Further details in regard to the making of iron ores need not be given here, but the conception of the necessity in many cases of a secondary

concentration before man may avail himself of the ores is of importance and one to be dwelt upon.

Hematite and the closely related slightly hydrous oxides are the commonest coloring matters of the rocks, giving rise to the color tones from red to brown. It is seen from this discussion that, where the oxide exists concentrated into workable beds of ore, it has passed ordinarily by the agency of organic matter through the soluble states necessary for its concentration from the originally disseminated state in the rocks. Where it is diffused, however, in a small amount, sufficient only to give its color to sandstones and shales, it has not necessarily ever passed into the soluble form, but may have been mechanically transported in a state of fine division along with the clay from the place of weathering to the place of deposition.

In the present stage of civilization, while the greater iron ore deposits of the world are being exploited, the iron oxide must either possess some special properties, or occur in large deposits and constitute as much as one-half of the whole rock mass, before it becomes of economic value. Not many decades ago, however, smaller and poorer deposits were utilized, and in a century or two, upon the partial exhaustion of the greater deposits, the smaller ones will again become of value.

Halite (as common salt is named technically by mineralogists) occurs in deposits of rock salt, frequently associated with gypsum, shales, and more or less calcium carbonate. It is sufficiently characterized by its taste and other physical properties given in Table II.

Gypsum begins to be precipitated from sea water when 37 per cent. of the water has been evaporated; but the salt in solution, although vastly greater in quantity, begins to be thrown down only upon the evaporation of 93 per cent. of the sea water. Salt deposits consequently only form in lakes or in lagoons which are nearly isolated from the sea and under conditions where evaporation greatly exceeds precipitation. They are geological marks, therefore, of arid climates.

The sodium in the original rocks is mostly locked up in the plagioclase feldspars. From these it has been set free by weathering, passing into solution in the forms of sodium bicarbonate and hydrous silicate, and on reaching the sea uniting with chlorine held

by magnesium, or in small part by calcium, and becoming transformed into salt. On account of its high solubility, it is thought by geologists that the salt deposited in the sedimentary rocks is of small amount in comparison with the salt in solution in the sea. The latter has increased from an unknown small percentage in the primeval ocean to its present amount of 2.9 per cent. by weight of the ocean water. Granting that these views are approximately true, the amount of salt in the ocean becomes a measure of the volume of weathering and erosion of igneous rocks, the original source of the sodium, through all geological time.

Potassium Minerals. — It will be noticed that in the tables no potassium salts are named among the minerals resulting from rock decay, although this element is nearly as abundant as sodium in the primary rocks. The reason why no potassium minerals in the derived rocks occur with the same frequency as halite is found in the greater resistance to decay which is shown by the primary potassium minerals, namely, orthoclase, muscovite, and biotite; also in the greater tenacity with which potassium in the form of hydrous silicate or carbonate is held in clay. As a result, the ocean water contains far less potassium than sodium, sea salt comprising but 1.1 per cent. of potassium as against 30.6 per cent. of sodium. Shales, the consolidated clays of former ages, contain, on the contrary, on the average about 3.2 per cent. of potassa as against 1.3 per cent. of soda. Potassium chloride is, however, highly soluble, so that only in a few localities has evaporation of the ocean water ever proceeded so far as to precipitate the chlorides and sulphates of potassium and magnesium as well as the chloride of sodium.

SOME MINERALS CHARACTERISTIC OF METAMORPHIC (ANAMORPHIC) ROCKS.

Preliminary Statement.

As stated previously in the introduction to this chapter, the metamorphic (anamorphic) rocks are made from either igneous or sedimentary rocks, through — first, development of pressures sufficient to induce rock flowage; or, second, heat sufficient to make unstable the old relations of molecules and therefore to

effect a new crystallization; or, third, the infusion of gases or liquids, which either by their mere presence permit of a freer and more stable adjustment of molecular relations, or which by bringing in some new substances or taking out old ones render a recrystallization necessary. In any of these cases a recrystallization is effected and new mineral species are apt to arise.

There are all gradations of metamorphism between the physical conditions which result in fusion and the formation of igneous rocks on the one hand, and those which produce rock decay and sedimentary rocks on the other. Consequently a more comprehensive way of viewing the subject is to regard metamorphism as including all rock changes. It is subdivided into — first, anamorphism or constructive metamorphism, embracing all those processes which by the aid of heat and pressure tend to build up complex silicate molecules and work in the direction of igneous rocks; and, second, katamorphism or destructive metamorphism, including those changes which break down the silicates, add water and carbon dioxide, and result in general in simplification of the molecules. The present discussion deals with the minerals resulting from anamorphism, commonly spoken of in elementary geological texts simply as metamorphism. In order to be consistent with that common usage, the word metamorphism is often used in this Bulletin where the word anamorphism would be more accurate.

In consequence of the conditions of heat and pressure which result in anamorphism, the common minerals of anamorphic rocks are the same as those given for the igneous rocks. In addition to these, however, a number of minerals occur which are characteristic of anamorphic rocks, owing chiefly to their peculiarities in chemical composition, and which, though not present in large percentage, are geologically important, on account of their conspicuous nature when present, and the frequency of their occurrence in small amounts.

Notes Supplemental to Table III.

Garnet. — Garnet is a silicate, the molecular composition of which may be resolved into the form 3 RO. R_2O_3. 3 SiO_2. As shown by the formula given in the table, R may stand for calcium, magnesium, or ferrous iron, and the mineral may con-

tain these three metals in various proportions. More rarely manganese also occurs. R_2 stands for either aluminum or ferric iron or various mixtures of the two. More rarely chromium or titanium may be present. Finally, in some cases the silicon is replaced in part by titanium. These variations in mineral composition, while retaining the same molecular form and consequent form of crystallization, give rise to corresponding variations in color and in quality. The colors vary even when the composition is nearly uniform. Within the group are found the following: colorless, clear deep red (forming precious garnet), yellow, green, and black. The common color, however, is some shade of red or brown. Garnets usually occur in well-formed, isolated crystals whose diameters in all directions are about equal, and with either 12 or 24 equal faces. Occasionally garnet occurs as a granular aggregate. The isolated crystals when developed in micaceous rocks are in many instances so closely enveloped in mica that the sharply bounded crystal form is obscured. The mineral then has the form of grains or lumps, and its true nature can only be demonstrated by a cross fracture. Often the garnet stands in strong color contrast to the background, since all the iron in the vicinity has been absorbed into the garnet in the growth of the mineral, and the immediately surrounding matrix is therefore apt to be free from iron-bearing minerals.

Garnet is sometimes present in basic igneous rocks, but is typically a metamorphic mineral generated at high temperatures in either contact or regional metamorphism. It appears to be formed with facility where heated vapors have escaped from igneous rocks into the surrounding formations and especially in the injected zone where igneous and metamorphic rocks are intermeshed. Garnet is hard and rather resistant to decay. These properties taken in connection with its high specific gravity cause it to collect in placer deposits with other heavy minerals, and result in its segregration with magnetite as streaks of black and deep red sand along those sea beaches which front coasts of metamorphic (anamorphic) rocks.

Tremolite and Actinolite. — These are amphiboles which, unlike hornblende, contain little or no alumina, and, in the case of tremolite, no iron, and, in the case of actinolite, a moderate amount of iron. Tremolite is formed by metamorphism of

sediments containing much lime, magnesia, and silica; if iron is also present in considerable quantity, actinolite is formed. Such little alumina as is present in the sediment goes into other minerals.

Tremolite is found especially in metamorphosed (anamorphosed) siliceous dolomites, occurring in distinct crystals either long-bladed, or short and stout in form, often in sheaves, sometimes fibrous. Its light color, the diamond-shaped cross sections, and its association with marbles serve to distinguish it from the other somewhat similarly shaped metamorphic minerals. The crystals are sometimes skeletal, enclosing within them more or less of the surrounding rock.

In actinolite the green is due to the presence of the ferrous iron. In the original sediments iron oxide is usually associated with considerable clay. The result is that actinolite is more commonly associated than tremolite with those somewhat more aluminous rocks which give rise upon metamorphism to schists. The actinolite is apt to occur in green, needle-like, matted crystals.

When in fibrous form and free from impurities, either tremolite or actinolite is known as asbestus, distinguished from fibrous serpentine by the presence in the latter of from 12 to 14 per cent. of water which can be driven off by ignition. The word asbestus, commercially used for two or three minerals, is thus seen to refer to a pliable and fibrous mineral form and not to a certain mineral composition.

Andalusite is seen from Table III to be a simple aluminum silicate and one of the relatively few minerals which are harder than quartz. It may be identified partly by its individual peculiarities and partly by its associations. Among the former, most noteworthy is the internal pattern often seen on breaking the crystal. This is due to the inclusion within the crystal of coloring substances as impurities during its growth. The coloring substances are not uniformly diffused, but concentrated along the diagonals of the section or in certain envelopes representing stages in the growth of the crystals.

Andalusite is developed in argillaceous schists as the result of the intense heat due to the presence near by of igneous masses. It is therefore a mineral characteristic of intense contact meta-

morphism, and, as seen from the composition as stated in the tables, may be made from kaolinite by the driving off of all water and the crystallization of the residue with separation of half of the silica.

Cyanite. — Cyanite is seen to be of precisely the same composition as andalusite but of an entirely different mode of crystallization, indicating a different molecular structure and different conditions of origin. The crystals form clusters of blades with flat sides owing to the possession of one perfect cleavage and another less perfect. In color the crystals are very commonly blue along the center shading into white on the margins. Occasionally gray and green varieties are found. Cyanite is often associated with garnet and staurolite, and is intercrystallized, frequently on a coarse scale, with quartz.

Besides andalusite and cyanite still a third mineral with the same chemical composition is known. This is *sillimanite,* occurring usually in needle-like forms, frequently in clusters, and often present in the quartz of gneisses. It is not sufficiently conspicuous or abundant, however, to be listed with the other most common or significant minerals, and is often associated with either one or the other of the more conspicuous minerals, andalusite or cyanite.

The conditions which determine the presence of andalusite or cyanite are found to be related to the specific gravities, which are as follows: —

Mineral.	*Specific gravity.*
Andalusite,	3.16 to 3.20
Sillimanite,	3.23 to 3.24
Cyanite,	3.56 to 3.67

Andalusite is formed under conditions of intense heat but where the pressure is not necessarily great. Cyanite, on the other hand, forms where the heat and pressure are both intense, and is hence associated with deep-seated igneous injections of granitic types and greatly mashed rocks. By crystallizing in the form of cyanite, the matter, becoming 12 per cent. denser, yields in an appreciable degree to the intense pressures. Great pressures, in general, favor the development of denser minerals.

Andalusite and cyanite, upon being brought near the surface

of the earth by the erosion of the overlying rock masses, may alter to talc, muscovite, or kaolin. By the dissemination of these alteration products through the crystal the latter may lose its original hardness, though preserving much of the original appearance. A lack of hardness should hence not by itself be given undue weight.

Staurolite is seen to be a silicate very high in alumina and possessing a moderate amount of ferrous oxide and water. It may be distinguished from tremolite by the somewhat flatter prism, the angle of the faces being 51 instead of 56 degrees; also by its color and luster, and the frequent habit of forming twin crystals, the two individuals crossing each other like the bars of a letter x. The twins stand at an angle of either approximately 60 or nearly 90 degrees to each other. The ends of the crystals are also symmetrically terminated and not obliquely, as in tremolite and other amphiboles. Staurolite may occur in many small lustrous brown crystals scattered through the rock, or in a few large ones, often twinned, which by being enveloped with scales of mica may acquire a lumpy character.

Staurolite is found in districts which have suffered intense regional metamorphism, being especially associated, like garnet, with schists and gneisses of sedimentary origin. Its highly aluminous nature is no doubt the cause of its frequent occurrence in the metamorphosed mudstones, the aluminous sediments. Like garnet, it is frequently built up under the intense conditions of its origin through the absorption of other minerals.

Epidote is seen from the table to be a silicate of lime, alumina, and ferric oxide; the two latter replacing each other and present in variable proportions. In addition, there is about two per cent. of water entering into the mineral composition as water of constitution. Epidote is low in its percentage of silica, which ranges from 35 to 39 per cent. In the common variety it is most readily recognized by its peculiar yellowish-green color, known as pistachio-green, because of which the mineral is sometimes called pistacite. Where epidote occurs in small fissures, in gas cavities, or in joint planes, it has usually a fibrous matted appearance, the mineral being distinguished from others of somewhat similar appearance by its freshness, its hardness, its brittleness, and its color. Where it occurs in the body of a

rock its usual habit is to form small scattered grains. Occasionally it is so abundant that these grains unite to form hard fine-grained rock masses. Sometimes it is found in altered feldspar and other lime- or iron-bearing minerals as a yellowish-green coloring substance, but without giving its hardness to the mass, owing to its occurrence with other and softer alteration products.

Epidote results especially from the alteration of lime and iron minerals in the presence of water vapor at a very high temperature. This is indicated by its presence as a common mineral in contact metamorphism; most abundantly where granitic masses have been intruded into impure limestones. The agency of the water is shown not only by its presence in small amount in the mineral, but also by the free crystallization of the epidote in joints and other cavities. It is found also in rocks which have been subjected to regional metamorphism, such as gneiss, mica schist, and hornblende schist. In such formations, however, it is ape to be inconspicuous owing to dissemination through the body of the rock.

Tourmaline. — Tourmaline is a complex silicate of boron and aluminum which includes also in varying proportions magnesia, iron, and alkali metals. Owing to the variable proportions in which the metallic oxides are present, the color may be black, brown, blue, green, or red. When clear and richly colored the mineral forms a gem, but the usual color is an opaque black. Tourmaline is peculiar in that the two ends of the same crystal are unlike, and it commonly occurs in prisms with a tendency to a triangular section. By the beveling of the edges the prisms may have six, nine, twelve, or more sides but without losing entirely the triangular aspect. In places tourmaline occurs in needle-like forms, but more usually columnar. It has no cleavage and is brittle, with the result that, where it has been crushed by rock pressure, it may be friable and present the appearance of soft coal. When in small or imperfect crystals, it may be difficult to distinguish from hornblende; but the lack of cleavage and the presence of triangular sections will usually serve to identify the mineral.

Tourmaline, though widely disseminated through anamorphic rocks, especially quartzites, is formed especially as an emanation

product from igneous masses, the boron and more or less of the other materials being carried off with the water vapor and other gases which escape from a magma when it moves upward to regions of less pressure and especially when it is undergoing crystallization. On reaching in the enclosing rocks a region of slightly lower temperature, the boron by combining with the other elements gives rise to tourmaline. It is hence found occurring with coarsely crystallized quartz and feldspar, in pegmatite dikes, or disseminated in schists and marbles near igneous masses, or sometimes in joint planes of metamorphic rocks at distances from any igneous mass.

Tourmaline is not to be rated as an abundant mineral, but from its significance and its conspicuous nature when present it deserves a place in the table.

Graphite. — Graphite is the common form in which carbon occurs in the metamorphic rocks, and may be distinguished by its softness and greasy feel, its color and its flakiness, the latter due to the existence of one perfect cleavage. Graphite in places forms valuable beds in gneiss, and is disseminated in small amount through many gneisses, schists, and marbles. There are consequently all gradations in its purity.

In such rocks it is the last stage in the metamorphism of organic matter, all but the residual carbon having been expelled by the extreme heat and pressure. It also occurs in microscopic flakes in meteoric irons and in terrestrial igneous rocks.

Chapter III.

THE IGNEOUS ROCKS.

VARIATIONS IN CHEMICAL COMPOSITION.

ACIDIC, INTERMEDIATE, AND BASIC DIVISIONS.

In the chemical variations which are found to exist in magmas, the percentage of silica is of special importance, since this is the most abundant oxide, commonly present in from 45 to 75 per cent.; and, since this oxide is the only one of acidic nature, it stands in opposition to all the others. The amount of silica is, therefore, universally employed to give the primary chemical basis of classification. Where it is so abundant that some of the silica exists uncombined with bases, the rock belongs in the acidic division; where the silica is in average amount so that it is all or nearly all in combination with other oxides, the rock belongs to the intermediate division; where silica is deficient in quantity so that there is an excess of metallic oxides, either free or combined with silica in highly basic silicates, the rock belongs to the basic division.

The lines between these divisions are drawn at 66 and 55 per cent., for reasons which are mineralogical, and which will appear in the following discussion.

Where there is much silica, the alkalies are also usually found in relative abundance, and the chief minerals of acidic rocks are the feldspars. But potash feldspar has 64.7 per cent. of SiO_2, pure solda feldspar 68.7, and pure lime feldspar (which, however, never occurs except in extremely basic rocks) has 43.2 per cent. Ordinarily, soda feldspar has a small amount of the lime feldspar combined with it, so that its silica percentage is seldom over 66. Consequently, 66 per cent. is the utmost amount of silica likely to occur in combination with the other oxides, and any excess of silica beyond this amount must crystallize as quartz. From this it follows that *acidic rocks may be generally recognized, if coarsely crystalline, by the presence of considerable quartz.*

The silica contents of the other common minerals are as follows: —

Muscovite, about . .	45 per cent.
Biotite, usually, . . .	35 to 40 per cent.
Hornblende, usually, . .	45 to 50 per cent.
Augite, usually, . .	45 to 50 per cent.

As either muscovite, biotite, or hornblende is almost always found to some extent in the acidic rocks, and as these minerals can hold only from 35 to 50 per cent. of silica, there will be some free silica developed as quartz even with a total content of silica amounting to only 66 per cent.

It may be further stated, therefore, that, although acidic igneous rocks are characterized by the presence of quartz, if the rock is nearly all orthoclase, it will be light in color, and two or three per cent. of quartz will indicate an acid nature, whereas, if considerable black mineral is present, as much as 10 per cent. of quartz would be necessary to indicate the same degree of acidity.

The intermediate division is characterized by the absence or almost entire absence of quartz and the dominance of feldspar or of feldspar with mica or hornblende. It is subdivided into two distinct groups, in one of which the sum of the three oxides, lime, magnesia, and ferrous oxide, is small in amount, giving rise to an essentially feldspathic rock; while in the other these oxides are present in large quantity, giving rise to a large amount of hornblende or biotite. The first group is known as the *syenite,* the second as the *diorite* family.

Fifty-five per cent of silica is chosen as the lower limit of the intermediate magmas because this is the silica content of the lime-soda feldspar which holds about an equal number of lime and soda molecules. This represents the average feldspar of the group. Consequently, if there should be less silica than 55 per cent. in the rock, there would not be sufficient when in combination with the potassa, soda, and lime, to form feldspars. Other and rarer alkaline silicates, such as *leucite* and *nephelite,* not given in the table of minerals, become substituted for the feldspars in progressively larger amounts in those varieties of rocks where the silica percentage sinks below 55. If there is

a large amount of the black minerals present, since they use only from 35 to 50 per cent. of silica, they allow a larger portion of silica to go to make feldspar; but, in proportion as the black minerals become abundant, the feldspar in consequence begins to take second place. On passing to the upper limit of the division quartz begins to be in evidence, at the lower limit either the basic alkaline silicates, such as leucite and nephelite, in the syenite family, or, in the diorite family, a dominance of hornblende or other dark minerals.

In the basic division silica is below 55 per cent., and the commonly occurring rocks are characterized by the dominance of black minerals. More rarely lighter colored rocks occur which show large amounts of the basic alkaline silicates or of the almost pure lime feldspar, but these are readily distinguished from the typical syenites, and need not be enlarged upon in an elementary megascopic treatment.

MAGMATIC DIFFERENTIATION AND PETROGRAPHIC PROVINCES.

In any region which has been the scene of prolonged igneous activity, rocks of acidic, intermediate, and basic chemical composition are all usually present. Even from the same volcanic center rocks of the most diverse silica content may flow at different times. The study of the sequence and composition of series of ancient lava flows has shown that at the beginning of an epoch of igneous activity the eruptions are apt to be of an intermediate composition, while toward the close of the epoch alternate eruptions of acid and basic character may occur. The last feeble outflow preceding extinction is commonly of basalt. To this cycle of igneous activity there are many apparent exceptions, some of which are due either to the fact that representatives of only a part of the cycle have been observed or to probable complications of cycles with subcycles.

These observations on the sequence of eruptives have led to a hypothesis of *magmatic differentiation.* This hypothesis holds that, when a magmatic mass stands fluid in a deep-seated reservoir for a geological epoch, a separation of the magma due to unknown causes takes place into unlike portions, analogous to the rising of cream upon milk. In this way is explained the

intermediate character of the initial eruptions and the highly acidic and basic character of the later. Such a view suggests that differentiation was prevented at an earlier time owing to a solid state of the rocks, and is in accordance with those lines of evidence which go to show that the earth is solid and rigid practically throughout its mass. The facts as to the actual variations of lavas are conspicuous and unquestioned, but the hypothesis of differentiation involves serious difficulties, since it is not known how, in large igneous masses, such a process can take place.

Although the eruptions of a particular geologic province may thus present striking variations from epoch to epoch, there is found running through all of them a subtle bond of affinity, recognized by marks of relationship which distinguish them from otherwise very similar rock types of other regions. This "blood-relationship," as it has been called, has given rise to the term, *"the consanguinity of rocks;"* and the fact that particular chemical and mineralogical marks are restricted to certain regions has given rise to the term, *"petrographic provinces."* Thus the earth's surface is divided into broad areas not always clearly limited, within each of which all the igneous rocks exhibit, in greater or less degree, some peculiarity.

To give simple illustrations, it is found that both acidic and basic rocks of certain isolated mountain groups in central Montana and western South Dakota possess an unusual proportion of alkalies in comparison with the igneous rocks of the regions to the west. As a still more striking fact, it is to be noted that in the western mountain systems of both North and South America the igneous rocks are associated with metalliferous deposits. In the eastern mountain systems, on the contrary, while igneous rocks are abundant, the metalliferous deposits are rare and comparatively poor in quality. On the basis of the relative proportion of alkalies to the sum of the lime, ferrous oxide, and magnesia in rocks of similar silica content, the whole world has been divided into two great regions of the Atlantic type and Pacific type of rocks respectively, the one relatively high in alkalies, the other in the other group of oxides. The limits of these regions appear to have shifted somewhat during the course of geologic ages, and each is broken up into provinces and these

again into districts within which the rocks possess some special resemblances. But even at one volcanic center local differentiation often results in basic and acidic types which, though superficially wider apart than the rocks of separate petrographic regions, are in reality closely related. The absence of a satisfactory theory as to the causes of these phenomena indicates how little knowledge has as yet penetrated into the deeper body of the earth.

MODES OF MINERAL AGGREGATION.

Rocks are sometimes composed of but one mineral, but usually consist of a mixture of two or more. These minerals may exist in various states of perfect or imperfect crystallization; they may occur of various sizes; their relations to each other may be alike throughout the rock mass, giving a massive formation, or they may exist in different relations in different parts, giving some structure, as bedded or gneissoid, to the rock mass. The fundamental features which serve to classify a rock are, then, chemical and mineral composition, texture, and structure. The chemical elements and the minerals entering in appreciable quantities into the composition of the outer portion of the earth have already been considered. It remains, therefore, to treat of those characters, namely, texture and structure, which become evident when the minerals are assembled in the rock mass.

DEFINITIONS OF TEXTURES.

Texture refers to the smaller details or features of a rock. It relates to the *fabric* of the rock, and is always evident in the hand specimen, as contrasted with structure, which refers to the variations either on a small or large scale which exist in the rock mass. The following textures are important in the megascopic study of igneous rocks: —

Glassy. — The fractured surfaces are smooth and more or less curved, like broken glass. The luster may be either vitreous or resinous. The glassy texture results from the lack of crystallization, even of a microscopic nature.

Felsitic or *Aphanitic.* — Felsitic means stony; aphanitic means without visible crystals. Both names refer to the texture of rocks which are largely or entirely crystalline, but on a micro-

scopic scale. The fracture surface, instead of being glassy, is more or less harsh to the feel and dull in luster. A piece of granite held at such a distance, as across a room, that the individual crystals are no longer distinguishable, presents an analogous appearance. Rocks with felsitic texture when free from decay may show many points of light upon a fresh fracture, owing to the numerous reflections from microscopic cleavage faces.

Granitic or *Phaneritic.* — Granitic texture is one in which the rock is wholly crystalline and on a scale so coarse that all the component minerals may be distinguished. The word phaneritic means that the crystals are visible, and is used to contrast such rocks with those of aphanitic texture. The word *granitoid,* meaning granite-like, is also sometimes employed.

Porphyritic refers to the texture of a rock in which the crystals are of two notably distinct sizes. The larger crystals give a mottled appearance to the surface which often makes such rocks valuable for ornamental building stones. The porphyritic texture arises from the overgrowth of one or two kinds of crystals in the rock mass, and must be carefully distinguished from that of rocks in which the larger portions are not crystals but angular or rounded fragments of other and earlier rocks. *Matrix* or *Ground-mass* is the name applied to the finer-grained portion of the rock in which coarser crystals or fragments are present. *Phenocrysts* means visible crystals. It is a collective name for the crystals of distinctly larger size than those of the ground-mass. A porphyry is thus made up of matrix and phenocrysts.

Pegmatitic refers to a still coarser crystallization than that of granites, this being the textural character of *giant granites,* better known as *pegmatites,* occurring as dikes associated with granite bodies. In size the average crystals of quartz and feldspar are typically an inch or more in diameter and exceptionally may be several feet in diameter.

ORIGIN AND SIGNIFICANCE OF TEXTURES.

The formation of crystals during the solidification of magmas is found to depend chiefly upon three independent conditions, being aided, first, by a deficiency of silica; second, by an abundance of water vapor; and, third, by slowness of cooling. The

slowness of cooling depends upon the volume and situation of the erupted magma and hence upon surrounding physical and geological conditions. It is this fact which gives texture such value as a basis of natural classification; but, since it depends upon other factors also, it must be used with caution and made subordinate to chemical composition.

Taking up these factors in detail, we note that silica in a pure state is one of the most difficultly fusible of substances, becoming pasty rather than molten at extremely high temperatures. Consistently with this character it is found to raise the fusion point of those magmas in which it is abundant and to decrease their liquidity when molten. The approximate range of the fusion temperature and the limits of high viscosity above the fusion point, as determined in the laboratory for the several divisions of rocks, are as follows:—*

Division.	*Fusing point.*	*Range of viscosity.*
Acidic	1250°-1350° C.	70°-90° C.
Intermediate	1150°-1250° C.	
Basic	1050°-1150° C.	30°-60° C.

In the molten state the various mineral molecules are intermixed and in a more or less unformed or dissociated state. When the temperature has sunk to that point where crystallization begins, the molecules must migrate through the fluid under the influence of the crystallogenic attractions to the point where the nearest crystal is forming. If the fluid is viscous and without circulatory currents, the molecules are able to move but very small distances and with great slowness, resulting in the building of many small crystals at minute distances, or even, as in a glass, forming no crystals at all.

Turning to the influence of water vapor, we find that it is abundantly present in most magmas, escaping in large volumes upon eruption, and therefore retained in larger quantity by those which do not come to the surface and hence give small opportunity for the water vapor to escape. Where it is abundant in magmas it is found to lower the fusing point of the mixture,

* The laboratory experiments do not exactly duplicate the conditions of nature since the water vapor is missing. Moreover, as has been recently shown, a definite fusing point is in many cases difficult to determine. Nevertheless the approximate values here given illustrate the influence of silica upon the nature of the magma.

and to greatly increase its fluidity. Furthermore, since most of the water vapor must escape either before or during the solidification of the rock, it promotes a movement of the portions in solution with respect to those portions already crystallized. It is thus a great carrier of materials in solution to growing crystals, enabling them to attain sizes otherwise impossible. Water vapor therefore promotes crystallization on a coarse scale; and, in those fissures where it has been escaping for long periods of time from large bodies of slowly cooling magma, it has built up in close relation to the parent bodies the coarsest crystallizations known in nature, those of *pegmatite dikes.*

Taking up the third factor for discussion, we see that slowness of cooling promotes coarse crystallization, since there is a longer time during which the crystals may form. Consequently molecules can move farther in proportion to the velocity and the strength of crystallogenic forces, to build the dominant crystals. The limit of coarseness due to slowness of cooling is seen, however, in the average coarse granite, since the more massive of these granite bodies have cooled so slowly that they have had practically unlimited time in which to solidify. In lavas, however, the surfaces and smaller fragments may be immediately chilled, and even the deeper portions of a lava flow will become solid in the course of a few weeks. The chilled portions will consequently show no crystallization of the mass, and the more slowly cooled portions will possess no more than a very fine-grained crystallization, except for the presence of such crystals as may have formed in the magma before eruption. As rapidity of cooling depends upon the difference of temperature between the hot body and its cold surroundings, the acidic lavas, since they have a higher solidifying point than the basic, are more quickly chilled. There are thus two contributory reasons, a more siliceous nature, and a more rapid cooling, which cause the acid lavas to solidify largely in glassy forms, which are, on the contrary, very rare among the basic lavas.

Since texture is seen to depend upon so many factors, it is obvious that no relation can be drawn with exactness between the texture and the geological occurrence; yet, in a general way, the two are related, as indicated in Table IV.

The porphyritic texture, as above defined, is due to two distinct causes.

1. The magma before coming into its final position may already have begun to crystallize and become charged with crystals of some size floating in a residual fluid. The latter is more rapidly cooled after eruption, solidification is hastened, and the result is a ground-mass of finer grain. There has been thus in many lavas a period of *intratelluric* (within the earth) and another of *extratelluric* (outside the earth) crystallization, giving rise to a porphyritic texture.

2. The formation of a coarse texture is not to be thought of as a result of a continued growing of only the final number of crystals, from initial molecules suspended in a fluid otherwise free from crystals, until they appropriated all the fluid and formed a solid and continuous mass of crystals of the final size. On the contrary, it is to be thought of as a competition among many small crystals, at first for the residual fluid between them and then for the material composing the crystals themselves. If the proper temperature is maintained for a sufficiently long time, the larger crystals increase in size by the absorption of their smaller fellows, the molecules being transferred by temporary solution in a very small amount of interstitial fluid. A concentration of the water vapor, such as seems frequently to occur near the borders of, and in the dikes proceeding from, a deep-seated magmatic mass, aids in this way very materially in the increase in size of certain crystals for which the conditions may be most favorable. It is thought to be in this way, by concentration of water vapor, that very large crystals of feldspar, sometimes an inch or more in diameter, may form, giving rise to granite porphyries. Conditions sometimes favor the overgrowth of other minerals also in this same manner, especially in the metamorphic rocks. A third factor sometimes connected with the development of two sizes of crystals in the same rock mass lies in the fact that at certain critical temperaatures minerals cannot spontaneously arise as new crystals from a fluid but can grow from such microscopic crystals as are already present. This condition if existing for some time may cause an abnormally large growth of such crystals, thus producing the phenocrysts of the rock. Then the cooling of the magma to a point where the fluid can spontaneously crystallize will produce the finer-grained groundmass.

Conclusion on Texture. — From this discussion it is seen that an acidic magma may, if it comes to rest at a depth in the earth, give rise to a granite cut by dikes of pegmatite. At another place it may show a coarsely porphyritic nature. If traced upward in imagination through the throat of an old volcano, the rock would be found to change its texture, the ground-mass becoming fine-grained. Finally as a lava flow it would be found to pass into a rock of microscopic grain or even one of glassy nature. Thus the widest differences in the appearances of igneous rocks may be due solely to the physical conditions surrounding the magma at the time of its solidification, the chemical composition remaining the same throughout.

STRUCTURES.

Structure refers to the larger features of a rock mass. It may or may not be evident in a hand specimen, but is always on a larger scale than the texture. In a large fragment or in a rock outcrop the structure is well revealed. It may be defined as embracing those features due to a systematic variation of the rock mass.

Spherical Structures.

These structures are often on so small a scale that they might perhaps be regarded as textures. Where rounded cavities arise they are due to the expansion of gas in the lava upon that relief from subterranean pressure which accompanies eruption. They must be distinguished in all cases from the usually more or less angular cavities which arise from partial solution of a rock.

A. Pumiceous, the finest of the spherical structures, is of a foam-like nature, named from pumice, of which it is typical. The cavities are very fine and closely packed, and occupy more than half the space of the rock mass.

B. Scoriaceous, or slag-like. — The cavities are larger, being individually visible, and are less abundant than in pumice, forming about half of the rock mass.

C. Vesicular. — The cavities are isolated and amount to distinctly less than half of the rock mass.

D. Geodic. — The cavities are lined, but not filled, with secondary crystals deposited from solution. When these linings

are of quartz, they are ordinarily more resistant to decay than is the surrounding rock, with the result that upon the erosion of the rock mass the geodes may give rise to hollow spherical stones remaining upon the surface.

E. Amygdaloidal, meaning almond-like, is the structure resulting when the spherical or spheroidal cavities of vesicular lavas become completely filled with secondary minerals. The structure must then be carefully distinguished from the porphyritic, which is the texture due to the presence of primary crystals (phenocrysts) of more or less angular form embedded in a finer-grained ground-mass. The commonest fillings of these cavities are quartz, calcite, and hydrous silicates; and the filling consists of mineral aggregates, not unit crystals.

F. Spherulitic is a spherical structure which arises, not from the formation of gas cells and their subsequent filling, but by a concretionary action which goes forward in glassy lavas, giving rise to small spherical crystalline spots which are frequently composed of radiating fibres. The superficial appearance may resemble the amygdaloidal but close examination will reveal clear distinctions.

G. Perlitic, resembling pearls, a structure also found in certain glassy lavas, but due to a spheroidal cracking, giving small grains with concentric coats.

Parallel Structures.

In these the rock is developed in one direction differently from another. In other words, it is uniform or homogeneous within a certain plane but not on a line at an angle to this plane. Such a parallel development, if due to a later mashing, is properly a metamorphic structure, and must be carefully distinguished in theory from one of igneous origin.

A. Flow Structure is the first to be considered. This is commonly found in glassy lavas, and is due to an original lack of homogeneity of the material and the flowing of the viscous mass, the two causes resulting in a banded effect. On account of the faster motion of some parts of the lava stream this flow structure is ordinarily minutely puckered and also thrown into larger wavy curves several inches or even several feet in radius.

B. Injected Structure. — Where an igneous mass has been

intruded into an older rock with strongly developed parallel structure, usually of metamorphic origin, the magma may penetrate in parallel dikelets through the whole of the older rock mass, giving rise to an injected structure.

Fragmental Structures.

Fragmental structures of igneous rocks occur in several forms as follows: —

A. Eruptive Breccias, made by the moving viscous mass breaking off fragments of the wall rock through which it comes. A present illustration is found in the lavas of Vesuvius, which always hold some included blocks of marble.

B. Flow Breccias are of much more common occurrence, and originate from crusts solidifying on the surface of a flowing lava stream and, through the further motion, becoming broken up and rolled into the still semi-molten mass. The fragments and the matrix will here be of the same kind of rock though the textures of the two portions are usually slightly different.

C. Explosive Breccias are formed by the outrush of material from the volcanic throat and the sudden expansion of gases within the semi-solid lava which is carried out, producing a complete disruption and fragmentation of the lava. Bombs are hurled in this way in violent eruptions to distances of some miles, and descend with large quantities of ashes, the latter largely of microscopic fineness and characterized under the microscope by sharp and angular edges. The bombs are more commonly somewhat rounded and rough. An explosive breccia may be distinguished from other kinds by the fact that the fragments are not embedded in a solid lava stream but in volcanic ashes; making a deposit much softer, more incoherent, and frequently somewhat stratified. Such explosion breccias are developed in enormous volume in places in the western United States.

Massive Structure.

Massive structure stands in contradistinction to all the preceding in being a homogeneous structure. Massive structure is characteristic of the interior of large igneous bodies, of which the granites are familiar examples.

THE PRINCIPLES OF CLASSIFICATION.

In all branches of knowledge it is necessary to apply names to individual things and groups of things, in order to give definiteness to thought; but the province of science consists not only in determining the nature of things and classifying them but also in investigating their modes of origin and relationships. For these reasons not only must names be given, but a system of classification is sought which shall express the state of knowledge in regard to the origin and relationships of the objects. This gives what is known as a *natural classification.* An *artificial classification* is one which, disregarding relationships, groups unrelated things together because of some unessential common character arbitrarily selected. A directory, for instance, is an artificial classification, in which names are placed according to the initial letters, whereas a natural classification would group them according to family and racial relationships. In science the effort is always toward natural systems of classification, supplemented of course by alphabetical indices. According to the degree in which a system of classification is found to be convenient and to express real relationships, it is successful and permanent. It is especially in the sciences dealing with organisms, botany and zoölogy, that such classifications have been elaborately developed, and several terms of progressively more inclusive meaning are habitually used. Beginning with the lowest one, these are: — individual, variety, species, genus, family, order, class, subkingdom, and kingdom.

These words have not been applied to the sciences of mineralogy and lithology. The reasons why such an accurate system has not been used is not because of lack of effort but because of the nature of the subjects. In lithology more than in any other branch of natural history has difficulty been found in obtaining a classification which should become universal and final. This is partly because rocks have not arisen like animals and plants by descent from simpler and now extinct ancestral forms, permitting a classification on evolutionary lines. Furthermore, rocks show all gradations from one species into related species so that the boundary lines of variety, species, and genus become arbitrary in position. With each refinement in the study of rocks, especially igneous rocks, new division lines have been

set up, new names invented for the subdivisions, and new meanings given to old names. This has been carried to such an extent that nothing short of a special glossary enables the student in this subject to keep in touch with all the names which have been proposed; and, as Professor Kemp has remarked, "The philological petrographer comes near to being the enemy of his kind."

The systems of classification of igneous rocks in particular have further been largely built up from characteristics ascertainable only through chemical analysis and the use of the compound polarizing microscope. Where this full information could not be had, there has resulted much guessing in the naming of rocks — a method which is naturally very unsatisfactory as well as unscientific.

Recently four of the more eminent petrographers of the United States, Cross, Iddings, Pirsson, and Washington, have met this difficulty by devising a very elaborate and entirely new system of classification for igneous rocks, based upon chemical and mineral characters, for the use of specialists, known as the "Quantitative Classification of Igneous Rocks," and have advised the use of a system of names much simpler and more uniform than the older nomenclature, for the use of geologists in other branches of the science, mining engineers, and others who have to deal with rocks in a general way. Thus two distinct systems of classifying the rocks according to the knowledge available seem to be needed.

The principles on which the simpler classification should be based are as follows: — Every character used in determining a rock name should be determinable by simple means and without the use of the compound microscope or chemical analysis. The characters should furthermore be well marked, essential, and not open to doubt. The classification should express real distinctions and relationships. The knowledge necessary to determine the name of the specimen should further be based wholly upon the *characteristics of the specimen,* and not involve any *inference* in regard to origin or to those geological relations which are evident only in the field.

The system here used for igneous rocks is to a considerable extent the same as that suggested by Cross, Iddings, Pirsson, and

Washington for field use, but varies from the latter by including some names in common use among mining engineers and others. The main divisions of this system are such as have gained international sanction through the usage of from fifty to a hundred years, but the limits of the divisions are adjusted to the requirements of determination without chemical analysis or the use of the compound microscope.

Igneous rocks show wide differences in chemical and consequently in mineralogical composition. The rapidity with which they cool and the presence or absence of water vapor result in similarly great differences in the size of the mineral particles and other characteristics of the rock. There are thus two lines, chemical and physical, upon which igneous rocks are classified, which may be likened to a series of horizontal and vertical divisions giving an arrangement of pigeon holes, as shown in Table IV.

A MEGASCOPIC CLASSIFICATION OF IGNEOUS ROCKS.

EXPLANATORY STATEMENT.

The preceding discussion of chemical and mineralogical composition, of textures and their origins, and of the principles of classification, has prepared the way for a natural classification of igneous rocks, based primarily upon chemical composition, secondarily upon texture. The result is expressed in Table IV, which will be readily understood after reading the preceding pages. To draw for the moment a parallel to the terms used in a biological classification, the igneous rocks are divided into four prominent *families* depending upon the chemical composition. These are the granite, syenite, diorite, and gabbro families. They are in petrology better known as *series*. Each family is subdivided according to texture into four *genera* which are, respectively, the fragmental deposits, the rock glasses, the aphanites, and the phanerites. There are thus in all sixteen subdivisions, some of which, however, as indicated by giving them the same names in the table, are indistinguishable by megascopic means. Each genus is subdivided into *species,* the more important of which are described in the following pages,

and certain of which have their names inserted in the table. In a more extended work than the present it would be appropriate to go to still greater lengths and describe the *varieties* found under each species. As noted previously, the terms genus and species are not commonly used in lithology.

In a column parallel with the column of textures, the usual geological occurrence is given, but this is to be regarded as additional information and not to be used in the rock classification; since not only are the modes of occurrence and textures not strictly correlated, but, furthermore, the determination of the mode of occurrence would require field investigation and frequently be impossible.

A brief discussion of the several groups and a description of the rocks composing them may now be taken up.

THE FRAGMENTAL IGNEOUS ROCKS.

Tuffs and Breccias. — These may occur with lavas of any composition, since they are caused by the sudden release of a large amount of occluded gases; the latter escaping as a result of that relief from pressure due to the lavas coming to the surface of the earth. But these fragmental forms are much more characteristic of the granite, syenite, and diorite families, than of the basalt; since the very fluid nature of the basaltic lavas allows the gases to escape rapidly without explosive action. Tuffs and breccias of basaltic nature are, however, abundantly known, and those of Vesuvius may be cited in illustration.

Tuffs and breccias are characterized by the fragmental structures of explosive origin already considered. Where the ashes have been drifted far by either air or water before settling, very fine-grained beds will be formed which have a chalky consistency. Where the vents have been numerous, however, and the material not transported after eruption, a heterogeneous mass will result. Such formations, thousands of feet in thickness, cover broad areas in the Rocky Mountains, and are especially well exposed in the canyons in the region of the Yellowstone National Park. In that region the amount of water erupted with the fragmental materials was so great that standing trees were buried without the wood being burned, giving rise to tier upon tier of fossil forests. The specific character of the whole mass,

whether rhyolitic, syenitic, or dioritic, may frequently be recognized by the included fragmental crystals and blocks of a crystalline nature.

Such breccia formations are usually deeply decayed, since each stratum was at one time a surface formation, and the porous nature permitted a free percolation of both rain and magmatic waters.

THE ROCK GLASSES.

Glasses may originate from magmas of either acidic or basic composition, but most abundantly from magmas of the granite family, and rarely from those of a basic nature. The reasons, which have already been discussed, are the more rapid cooling of the acidic magmas upon extrusion and their more viscous nature when near the solidifying temperature; both factors hindering the crystallization and consequently the formation of definite minerals. As a result, large masses of rhyolitic obsidian are sometimes found, as in the Obsidian Cliff of the Yellowstone National Park.

It is important to note that the color of a rock glass, unlike that of the crystalline rocks, is of no significance in classification. The reason for this is seen on considering a more familiar but parallel case. A few small particles of India ink would have no coloring effect in a block of ice, but upon being dissolved in the water from the melting of the ice would color the whole deeply. In the same manner the iron oxide which would contribute to a few crystals of biotite in a crystalline rock and result merely in a white granite speckled with a few dark flakes of mica, when diffused through a rock glass will give even a rhyolitic glass a deep color; and this color may be brown, red, or black, according to the chemical form of the oxide.

All glasses retain their luster for a brief geologic time only. In ancient formations, that is, those which have been preserved by burial and later exposed by erosion, the glass has undergone a microscopic crystallization *en masse* which gives a fractured surface the appearance of ground glass or flint. The color may still remain of some deep tone, though there is a tendency toward pale green. This transformation of glass into microscopically crystalline rock which takes place with burial during long periods of time is termed *devitrification*.

Porphyritic textures are common, especially in the acidic and intermediate divisions.

The glasses comprise a number of kinds, which grade into each other, the particular kind depending upon the structure, fracture, and luster.

Pumice is a rock froth, consequently white and able to float upon water. The individual gas cells are for the most part extremely small.

Scoria. — In the basalts, on account of the greater fluidity while molten, the gas cells have largely run together, making fewer cells but of larger size, and giving a slag-like appearance to the rock. This form is called *scoria.*

Obsidian is the name of the clear glassy varieties. Flow structure is usually marked and spherulitic structures are common. The luster is that of glass, and the fracture is conchoidal — also a glass-like characteristic. They are, in fact, natural glasses.

Pitchstone differs from obsidian in possessing from 3 to 10 per cent. of water which has not separated from the magma upon solidification. It gives the glass a pitchy or resinous luster and a rougher splintery fracture than that exhibited by obsidian. There is also an absence of the keen cutting edges of the surfaces of fracture, and the rock is softer.

Perlite is an obsidian or pitchstone characterized by small spherules resembling pearls, whence the name. See also *Perlitic Structure,* p. 75.

Basaltic Obsidian, or *Tachylite,* may be distinguished from other obsidians by its occurrence as thin crusts on basalts, and its easy weathering, giving stains of iron rust.

THE APHANITIC LAVAS.

The bulk of extrusive igneous rocks fall under this division and the rocks of many thin dikes also. They are characterized by a microscopic crystallization which is frequently incomplete, more or less glassy matter being intermeshed. Quite commonly all the crystals present are too small to be identified with a lens, and nothing but an examination of a thin section with a compound microscope will determine the relative amounts of quartz and feldspar in the lighter colored kinds. Hence a general name must be employed for all such rocks which must not involve uncertain inferences in regard to composition.

Felsite is the name employed for this purpose, and includes all the fine-grained and light colored forms.

Basalt is the term used for the grayish black forms.

Felsites, however, are in many instances porphyritic; and when the phenocrysts are sufficiently abundant to make known the mineral composition with some degree of accuracy, the rock may be further classified. Thus, when many quartz crystals are visible, the rock may be at once classed as porphyritic rhyolite, also known as quartz porphyry. Under the older chemical schemes of classification it would still be necessary to determine whether the feldspar was a potash or a lime-soda feldspar, the latter making the rock a *quartz andesite* and not a rhyolite. But the determination of the kind of feldspar as a means of classifying rocks megascopically must be ruled out, so that all quartz-bearing feldspathic lavas should be called rhyolites and none called quartz andesites.

Rhyolite, trachyte, and andesite are terms in common use and understood by all geologists and mining engineers. It seems desirable, therefore, to define these names for megascopic use as follows, although they may be employed with safety only where the nature of the lava is pretty well known.

Rhyolite in megascopic lithology includes all felsites which can be clearly seen to contain much quartz. This may be in very small crystals or in scattered larger crystals, the latter, as above noted, giving the name of *rhyolite porphyry,* or *porphyritic rhyolite,* sometimes known as *quartz porphyry.* The rhyolites usually show a strong flow structure, and on weathering are apt to give rise to platy fragments. They may grade into the various glassy forms, and are commonly somewhat altered, showing colors varying from pink to red or brown and sometimes orange, the color being due to diffused ferric oxide in small amount.

Trachyte in megascopic lithology is essentially a feldspar lava. There is no indication of quartz, and the dominance of feldspar is indicated by a light color and the presence of a minutely rough and splintery texture due to the intercrystallization of small crystals of feldspar of a prismatic form. The fresh surface has a particularly harsh feel to the fingers on this account. There are frequently phenocrysts of feldspar, but, as these may occur also in rhyolite and andesite, that fact alone

is not sufficient warrant for naming a rock a trachyte. Trachytes are relatively rare as compared to rhyolites and andesites, though common in some districts. Under the usual definitions a trachyte must consist of an *alkali* feldspar.

Andesite is the commonest form of lava in the Cordilleran regions of North and South America, and was named from its dominance in the Andes. Megascopically defined, it is a rock consisting of feldspar and hornblende, with little or no quartz. Both the feldspar and hornblende may exist as phenocrysts, giving andesite porphyries. Andesite grades into the other groups and hence may vary considerably in color, the typical color being gray. The hornblende may be replaced by biotite or augite.

Basalt is a basic lava commonly called black in color. In reality, however, no rock save coal is jet black, and basalt is rather a dark gray. When weathered the color may change to light gray or brown, and often shows rust-colored surfaces. The texture in basalt is usually more uniform and more rarely porphyritic than in the other lavas, but vesicular and scoriaceous forms are common. These basic lavas are very fluid when molten and frequently give rise to quiet flows which, if in sufficient volume, may extend to great distances from the vent — distances of from fifty to one hundred miles being known. In connection with these facts it is to be noted that basalts have contributed more than any other kind of lava to the great lava fields of the world. Further, the central portions, upon solidifying, often show a well-developed columnar structure, explained in text-books on geology. *Trap* is a convenient and well-known name used for a dark colored igneous rock which may occur either as a surface flow or in dikes. It includes both basalt and the somewhat coarser-grained form known as diabase.

THE PORPHYRIES.

Where the porphyritic texture is conspicuous it should find recognition in the name. There are several accepted ways of doing this: First, the word porphyry may be added to the rock name, as, felsite porphyry, rhyolite porphyry, granite porphyry. Second, if the porphyritic state is not so marked or is subordinated to some other prominent feature, the word may be

used as an adjective, thus — porphyritic obsidian, porphyritic basalt. Third, where the phenocrysts are more prominent than the matrix, the name may take cognizance only of the mineral of the phenocrysts, thus — quartz porphyry, feldspar porphyry, hornblende porphyry.

It will be noticed that the first two modes of naming are applied to different degrees of the porphyritic nature. Both are acceptable when well chosen. The third mode, however, is not good, since the name tells nothing regarding the rock save the kind of mineral which occurs as phenocrysts; whereas, a name should express the utmost possible amount of information in regard to the rock.

THE MICROPHANERITES.

The coarse-grained rocks on the one hand and the lavas on the other are clearly distinct from each other, the one group solidifying far below the surface of the earth, the other solidifying upon the surface. Between these two a third group of rocks is found originating under intermediate physical conditions. They are rocks which have cooled under some pressure and with some degree of slowness, resulting in the absence of porous or glassy states and the development of a crystalline texture coarser than that of the aphanites. The individual crystals may be seen, yet they are not of a size to permit their ready study and identification. Rocks of this grain frequently occur in the less massive and more superficial intrusives, such as dikes, sills, and laccoliths. They have sometimes been called, especially by the Germans, "the dike rocks." Such a term, however, involving the geological mode of occurrence in the rock name, is objectionable; since thick lava flows as well as laccoliths may exhibit the same texture as the dike rocks. Another general term which has been applied is that of "the porphyries," but this is still more objectionable, since porphyritic textures are frequent in both glassy and granitoid igneous masses and have no relation to the fineness or coarseness of the ground-mass.

On account of this confusion in their treatment and the absence of sharp demarcation from the aphanites on the one hand and the phanerites on the other, some authors have dropped the group entirely. Such transitional rocks constitute, however, a

real fact of nature, and as such should be recognized in the scheme of classification. The writer knows of no better term for these rocks than microphanerites — a term which expresses their intermediate character. *Microgranite, microsyenite, microdiorite* will accordingly be the three names to be given to rocks of the acidic and intermediate groups when of this degree of coarseness of grain, requiring a simple lens for the separation of the minerals. These names, which are at the present time occasionally employed, would seem to deserve a wider currency.

A well recognized type of microgranite is known as *aplite,* occurring as very light colored dike rocks possessing a fine even granular texture resembling that of loaf sugar. They may vary toward felsites on the one hand or porphyries and pegmatites on the other. They consist of quartz and feldspar with usually a little white mica in fine flakes. The dikes of aplite cut granite masses or more rarely the associated wall rocks, and are usually closely related in origin to the associated granites.

Diabase, the basic rock falling in the group of the microphanerites, is a well recognized rock type. In true basalt the grain is even, the minerals too small to be individually seen, and the microscope shows that a greater or less amount of uncrystallized material is also present. In thick surface flows, however, but more typically in dikes and intruded sheets, the crystallization is sufficiently coarse to be visible and the scoriaceous character disappears. The individual crystals are not distinguishable by the naked eye, but it is readily seen that the rock is entirely crystalline. Moreover, as best seen by the microscope, the small crystals of feldspar dominate the crystallization, giving a peculiar texture consisting of a minute pattern of straight gray feldspar prisms with the black minerals filling up the angular interspaces. This texture is sometimes best revealed in a weathered specimen. The columnar structure is frequently strikingly developed, the mass being cracked into more or less regular prismatic columns roughly averaging a foot to several feet in diameter. Diabase is occasionally porphyritic, giving rise in that case to the name of *diabase porphyry.*

Trap. — Diabase grades on the one side into fine-grained gabbro, and on the other into basalt. Microdiorite may also approach this type in general appearance, although in reality quite

different chemically and microscopically. There is needed therefore some general term for a fine-grained dark rock which, when definite information is lacking, should not receive a definite name. Dolerite (the word meaning deceptive) is a term somewhat in vogue in Europe for ths indefinite use, but trap is a popular term which already exists in English and which therefore seems preferable to dolerite.

THE PHANERITES.

These, as previously defined under texture, are rocks in which all the crystals are visible and distinguishable.

Granite, the commonest form, is readily recognized by the presence of quartz with feldspar. Following the general rule, the species of granite are named according to the subordinate minerals which are present, and varieties are named according to the texture and structure. Thus a quartz-feldspar phanerite in which biotite is the subordinate mineral would be called a biotite granite. If, furthermore, the rock were unusually fine-grained and dark gray, these varietal characters would be expressed by saying that the rock was a fine-grained and dark gray biotite granite.

The commonest species of granite are muscovite, biotite, and hornblende granites. The commonest varieties are white, pink, red, and gray in color; and fine, coarse, porphyritic, and pegmatitic in texture.

Pegmatite is a coarse-grained form, discussed under the subject of texture, which is usually found in veins or dikes associated with igneous or metamorphic rocks. The pegmatites are the commercial sources of feldspar and mica. Where the pegmatitic texture is only moderately developed, and the rock occurs in broad masses rather than in dikes, the pegmatite passes into pegmatitic granite. Pegmatites represent a transition between the crystallization of a solidifying magma and the crystallization of vein minerals from water solution. As the magma crystallizes, water vapor and other volatile substances can only enter into a very few of the minerals which form at the prevailing temperature and in those only to a small per cent. These volatile constituents aid however in carrying forward the crystallization into which they cannot enter, from which fact they are known as mineralizers. Where present in abundance they pro-

duce a very coarse texture. Consequently, as the crystallization of the magma goes forward, the residual liquid acquires an increasing proportion of the volatile substances, finally becoming a solution of magma in water, rather than a solution of water in magma; the two being found to mix in all proportions at these very high temperatures.

Certain of the rarer elements as well as the constituents of quartz and feldspar stay with the residual solution. The latter tends to escape into fissures and may penetrate by such means the overlying rocks. There in the cooler enveloping zones the mineral substances are progressively precipitated, the water and gases ultimately escaping. Thus it is seen that, owing to this process of the expulsion of the mineralizers from a magma, very coarse-textured dikes or veins arise, which consist chiefly of feldspar and quartz, minerals of igneous rocks, but in which there tends to be some segregation and banding of minerals as in the formation of fissure veins from water solution. Many rare minerals and certain gem-stones also occur in these pegmatite dikes or veins.

Two notable varieties of pegmatite are —

A. Giant granite, in which the individual crystals are several inches or even a foot or more in diameter; and —

B. Graphic granite, in which the feldspar occurs in large crystals which have dominated the crystallization, and the quartz occurs in small regular inclusions scattered through the feldspar and arranged parallel with each other in such a manner as to suggest (when seen in cross section) writings in Hebrew or Assyrian characters.

Syenite is essentially a feldspar rock, and, like granite, includes species which are named according to the subordinate mineral present. Thus, muscovite, biotite, hornblende, and augite syenites are examples.

Diorite shows an abundance of both hornblende and feldspar and but little or no quartz. When the feldspar sinks to the rank of a subordinate mineral, the rock passes over into the basic group. Diorites, like syenites, are divided into species according to the subordinate mineral or minerals which are present.

Gabbro is characterized by the dominance of dark minerals, several important subdivisions being made in cases where one particular mineral makes up the bulk of the rock mass. Thus: —

Pyroxenite is a rock consisting in large part of pyroxene. *Hornblendite* is one consisting of hornblende. Usually in this case there has been alteration from pyroxene attended with rock mashing; and, if a parallel structure is present, either from the original crystallization or from mashing, the rock becomes *amphibolite*. *Peridotite* is a rock consisting of pyroxene and olivine, each in conspicuous amount. Other species also exist but hardly in such abundance as to warrant their definition in a work of elementary character.

Chapter IV.

THE SEDIMENTARY ROCKS.

INTRODUCTORY STATEMENT.

The identification of the species of sedimentary rocks and the understanding of their significance and mode of origin depend upon the recognition of the texture, structure, and mineral composition, and the processes by which these have been attained. As in the case of the igneous rocks, the distinctions and relationships must be expressed by a natural system of classification. To meet these requirements tables are appended which give the names of the chief rock types, and also their distinguishing features and modes of origin. Textures, structures, and principles of classification, the latter based on mode of origin, must, therefore, be discussed in sequence.

TEXTURES.

Textures in sedimentary as in igneous rocks depend upon the size and shape of the units of which the rock is made. Texture should in all cases be distinguished from the idea of softness or hardness, and refers merely to the character of the constituent grains as shown on a fractured surface. The several sedimentary textures to be defined are as follows:—

Clastic rocks are those made of fragments of older rocks, the word meaning broken. These fragments may be individual minerals or aggregates of minerals, and they may be unworn and angular, or rolled until reduced to spherical or spheroidal forms. The purely clastic textures are, therefore, comparatively coarse-grained, and result from mechanical disruption of an older rock mass followed by mechanical transportation and accumulation. In proportion as the rock fragments are finer, chemical activities have had greater opportunities, so that to the microscopic textures the term clastic is less strictly appropriate. The

particles in that case are more in the nature of chemical residues or precipitates. Clastic textures are subdivided as follows: —

A. Brecciated rocks consist of angular fragments of pebble size or larger. Such fragments speedily lose their angularity upon transportation; and are therefore characteristically found at the base of cliffs, occurring as talus breccias; or swept by rains rather than streams to limited distances, as wash slopes. As such they may constitute alluvial cones.

B. Morainic texture refers to the grain of material transported by ice and not sorted and rounded by flowing water. The northern portions of Europe and North America are largely covered with a mantle of ground moraine, commonly called *till,* left upon the retreat of the continental glaciers of the recent ice age. The texture of this deposit is characterized by polyhedral stones and pebbles with rounded edges and angles, and often with polished and striated and flattened sides, set in a matrix of sharp sand grains masked by the presence of silt and clay. The deposit is therefore characterized by having been subjected to shoving and grinding, but not to rolling or sorting.

C. Conglomeratic refers to the texture of consolidated gravel deposits, characterized by the more or less complete rolling of the pebbles by currents of water, the interstices becoming filled with sand. There are all gradations between brecciated and conglomeratic textures; but, where rolling and wear is evident, even though the pebbles be not round, the term conglomeratic should be employed. The term conglomerate applies to clastic rocks to a lower limit where the pebbles are as small as a twelfth of an inch in diameter.

D. Gritty as a texture refers to coarse sand of an angular nature, sorted by currents, which, however, are much less efficient in rounding small particles than in rounding fragments of larger size. When such a sand is consolidated into rock the surface of a recent fracture gives a harsh feel to the fingers.

E. Sandy texture differs from gritty in that the particles are rounded to some degree, though it may be slight.

Referring to textures of other than a clastic origin, *porous, cavernous,* and similar descriptive words need no definition.

Microcrystalline, granular, fibrous, earthy, and similar words refer to the character of the texture in deposits of chemical origin.

Oolitic texture refers to rounded grains of chemical and concretionary origin, the grains having become cemented into a solid rock resembling a mass of fish eggs. It occurs in certain limestones and also in some deposits of limonite. More rarely it is found in limited deposits of a siliceous nature.

STRUCTURES.

Sedimentary structures may be grouped under three heads, as massive, stratified, and concretionary.

Massive structure is that in which uniformity of composition is found in all directions. Its definition is the same as that of massive in the structure of igneous rocks. It is significant of unchanging conditions of transportation and accumulation during the formation of the deposit. It is found more especially in clays laid down in continuously quiet waters and in the glacial deposits formed directly by the ice.

Stratified structures are typical of sedimentary rocks, and result from a variable supply of material or variable strength of current working on heterogeneous material. The tidal cycle, the storm cycle, and the cycle of the seasons, by varying the power of the transporting agencies, give such results; not to speak of those longer variations in climate or in geography the knowledge of which is based upon geological evidences. As a result of these cyclical variations, strata consisting of different sizes and kinds of material are laid down in succession, or previous strata are eroded and others laid down in new positions. The chief varieties of stratified structures are as follows: —

A. Laminated. — Very thin and regularly bedded. The result of quiet but variable deposition, often chemical in nature.

B. Shaly. — Thin-bedded but with more or less irregular layers, splitting readily into laminæ which do not have a smooth surface. Typically, the structure of deposits of sandy clay which show slight variations in successive layers.

C. Thin-bedded, as in flagstones. Well-defined layers, thicker, more regular, and more persistent than in the shaly structure. Characteristic of fine-grained muddy sands laid down over level bottoms, also of argillaceous limestones.

D. Thick-bedded. — Strata a foot or more in thickness, a condition necessary for building stones. Characteristic of rapidly-

formed deposits, as in sandstones, or of slowly-formed deposits subject during deposition to equally slow variation in conditions, as in the purer limestones.

E. Obliquely-bedded. — Thick strata, the component laminæ of which are inclined to the planes bounding the strata. Frequently characteristic of sands laid down rapidly by currents in very shallow water.

F. Cross-bedded applies to layers which cross each other at various angles, the later cutting out the earlier at the places where they intersect, the result of "scour and fill" by currents shifting in place and in intensity. Especially characteristic of rivers and estuaries among water-laid deposits. Accumulations of wind-blown sands in the form of dunes show this structure to a remarkable degree.

G. Flow-and-plunge Structure. — An accentuated form of cross-bedding, made by tumultuous currents, but without the regularity and large scale of the cross-bedding developed in the accumulation of wind-blown sands.

Concretionary Structures. — Concretions are irregular or rounded aggregates of mineral matter without an external crystal form. The internal structure is either fibrous, microcrystalline, or amorphous. In size they range from a fraction of an inch to some feet in diameter. Concretions have originated by the aggregation within the solid rock of an originally diffused and slightly soluble material. The structure depends on three conditions: — First, there is always a small amount of moisture in a rock. Second, this moisture, from its intimate diffusion through the rock, is always saturated with mineral matter in solution, although the amount so dissolved at any one time is small; the point of saturation for the common rock materials being very low. Third, the amount which can be held in solution is slightly lower in the presence of large crystals or aggregates of the material in question than where this material is in a diffused form. This is due to the attractive power which a crystal exerts for molecules of its own material which may be in the adjacent solution, by the annexation of which molecules the crystal grows.

The interstitial water in a rock tends thus to become saturated by dissolving especially the diffused and amorphous material. This solution is then slightly depleted by the larger aggregations

of that material and re-enriched by the further solution of the same material in other parts of the rock mass. In the crystalline rocks this action results in the growth of crystals to a certain limiting size. In the sedimentary materials it is a potent cause aiding in the cementation and solidification of loose sediments, and by being carried further results in the development of concretions. The concretionary structure is shown most frequently in the formation of calcareous concretions in argillaceous rocks, ferruginous concretions in carbon-bearing argillaceous rocks, and siliceous concretions in calcareous rocks.

THE PRINCIPLES OF CLASSIFICATION.

The materials which make up the sedimentary rocks are derived from the erosion of the lands, and are carried greater or less distances and sorted by the carrying agents during the transportation and accumulation. In so far as the erosion and transportation have been accomplished by purely mechanical means the original minerals will not be chemically altered. Erosion, however, depends largely, except in deserts and upon lofty mountains, upon a previous rock decay by which new chemical compounds are made and the cohesion of the old rock mass is lost. During this process a part of the rock goes into solution, and is transported in that manner, to be again transformed into rock through chemical precipitation, either with or without the agency of living organisms. This gives rise to the division of rocks originating from material in solution into organic and inorganic sections.

The causes of the differences in sedimentary formations are found to be fundamentally due to the differences in response of the minerals of the primary rocks to the chemical activities of rock decomposition. Ultimately, therefore, the problem of the sedimentary rocks, like other problems in nature, depends upon the fundamental sciences of chemistry and physics. This leads to a fundamental *chemical* classification for sedimentary as for igneous rocks. In the sedimentary rocks we have the three great groups of sandstones, mudstones, and limestones, respectively; with three subordinate groups, one for the iron ores, one for the salts of alkali metals resulting from evaporation, and one for the carbonaceous deposits.

A subordinate or cross classification can also be made, as in the igneous rocks, depending upon the *physical* conditions which accompanied the derivation, transportation, and accumulation of each particular deposit, these conditions expressing themselves in the sedimentary textures and structures previously discussed. Two primary divisions may be distinguished in the physical conditions governing sedimentation: —

First, the material is carried by mechanical forces and accumulated in molar aggregates, that is, in fragments larger than molecules.

Second, the material is carried in a state of molecular or even submolecular division, that is, in solution. Since solution involves either the evolution or absorption of heat and the atoms of the molecules are to some extent dissociated, this partakes of a chemical nature, and is called a physico-chemical process.*

Each major division of sedimentary materials resulting from these two modes of carrying (in a state of fragmental or a state of molecular disaggregation) may again be classified into two subdivisions.

In those aggregates, such as deposits of sand or mud, resulting from mechanical forces there are: —

A. Those in which the material is transported, as is gravel and sand, by shoving and rolling while resting on the bottom, and —

B. Those in which the state of division of the material is so fine that, in spite of its greater specific gravity, it is floated in an agitated medium, and settles from a state of suspension when the medium becomes quiet, as dust from air and clay from water.

On the other hand, in that major division comprising sedimentary deposits which have been made from material in solution, the material may be taken from solution: —

C. By inorganic chemical means; that is, by chemical interaction of unlike solutions, as river and sea water; or by saturation and precipitation, as in evaporating sea and lake waters. This is geologically the more primitive mode by which the

* Physics is the science dealing with the relations of matter and energy with molecules as units. Chemistry is the science dealing with the relations of matter and energy with atoms as units, chemical changes leading to the unmaking of old and the building up of new molecular states.

slightly soluble materials have contributed to the sedimentary formations, but is not now, nor has it been since the dominance of life on the earth, the prevalent method.

D. The second subdivision of chemical deposits is that comprising those formed through organic agency, the material being taken out of solution and changed into solid form within or about the organism. Being but slightly soluble, it accumulates through the death of the organisms faster than it is dissolved by the surrounding slightly unsaturated water. In this way have accumulated most calcareous and ferruginous deposits which occur as formations in the sedimentary rocks. Carbonaceous deposits are also formed in a somewhat analogous way and may be grouped here.

Deposits of siliceous, argillaceous, ferruginous, and calcareous nature are known to be accumulated through both organic and inorganic chemical agency; but, on account of the highly insoluble nature of the siliceous and argillaceous materials resulting from rock decay, the vast majority of these deposits are of mechanical origin,* while ferruginous and calcareous deposits show a great predominance of chemical and, furthermore, of chemical-organic origin in their primary deposition, occasionally modified by re-solution and re-deposition.†

Deposits rich in magnesia, potash, and soda, on the other hand, are always, at least in their initial form, dependent upon chemical and inorganic causes, their great solubility doubtless preventing their utilization in the solid structure of organisms, since they would be continuously dissolved in the body fluids.§

* In fact the only deposits known in which an appreciable part of the argillaceous matter is of organic origin are the red clays of the abyssal sea bottoms. There the lime is dissolved as fast as it is deposited, so that ultimately the traces of organic alumina become appreciable, though mixed with dust of inorganic origin.

† In general it may be said that calcareous and ferruginous deposits originating by precipitation within the crust arise through inorganic reactions, while those originating at the surface are the result of life processes. Iron ore deposits in most cases however involve also an indirect organic origin, as discussed under the minerals *siderite* and *limonite*. It is chiefly through the deoxidizing action of dead organic matter that the iron is carried in solution to the place where it is concentrated.

§ Magnesium in the form of carbonate is an exception to this statement, but the forms in which magnesium is found in solution in sea water are prevailingly the highly soluble chloride and sulphate, while calcium prevailingly occurs as the bi-carbonate or sulphate, both of which are only slightly soluble.

DESCRIPTIONS OF SEDIMENTARY ROCKS.*

MECHANICAL SEDIMENTS.

Visibly Granular.

Talus Breccias. — Described previously under texture. In mountainous regions such breccias mantle the slopes at angles up to 35 degrees, and, when loose and coarse, are known as slide rock. Varieties are named according to the nature of the rock fragments of which they are composed, as a limestone breccia, or a quartzite breccia. Through gravitative creep, rain, daily temperature changes, and frost action, such slopes at a distance from the cliffs flatten out to a low angle and the material becomes of finer grain.

Glacial Drift. — Described previously under texture. Marked especially by the presence of erratics — that is, stones of some size which are unlike the neighboring bed rocks, and have been transported perhaps for hundreds of miles from the parent ledges. The material is of all sizes, packed together without order, and giving evidence of no transportation by rolling or sorting by water. It occurs in regions of present or past glaciation. In its loose state as a surface deposit of the recent ice age it is called *till,* and where consolidated into rock, the product of more ancient glaciation, has been designated as *tillite.*

Conglomerates. — Consolidated gravel, usually interbedded with sandstone strata. The pebbles are most commonly of silica, since quartz in its various forms is the most resistant of the common rock-making minerals to both chemical and mechanical forces of destruction. Where the pebbles have suffered but limited transportation, they may be wholly or in part of other materials. The various kinds of conglomerate may be named according to the nature of the pebbles, and secondarily qualified according to the nature of the matrix. Thus a conglomerate of quartz pebbles embedded in a highly ferruginous matrix may be called a ferruginous quartz conglomerate. Conglomerates indicate rapid erosion largely of a mechanical nature.

Sandstones originate from consolidated sands, and even more than conglomerates consist dominantly of quartz grains. Various kinds of sandstones may be defined as follows: —

When these grains are coarse and sharp, the sandstone is called a *grit.*

* Supplementing Table V.

When the grains consist in part of feldspar, the stone is called an *arkose* or, more simply, a *feldspathic sandstone.* Such deposits accumulate most abundantly in arid climates, since only in the presence of moisture can feldspar decay. Rapid erosion, by not giving sufficient time for decay, may also lead in some degree to the making of arkose. Sands usually contain some clay, iron oxide, or calcium carbonate, as a filling between the quartz grains, and the presence of these materials in either the incoherent or consolidated sands may be indicated by adjectives; as, an argillaceous, ferruginous, or calcareous sandstone.

Invisibly Granular.

Loess and *Adobe.* — *Loess* is formed of an impalpable silt containing but a small proportion of true clay and no sand. It is made by mechanical rather than chemical disintegration of the parent rock masses, with the result that it still contains a large amount of the soluble constituents, and with proper watering forms a soil of great and lasting fertility. The material may be transported either by winds from desert regions or by slowly moving waters from regions of glaciation; the loess of China being due to the first cause, the loess of the central United States largely due to the second. But the Chinese loess has been in part redistributed by water, and the American loess has been redistributed and swept beyond the river valleys by wind. It forms light yellow or pink deposits which, when semi-consolidated and dissected by erosion, present steep and persistent bluffs, not rapidly weathering down in the manner of other earthy deposits.

Adobe is the name of the valley deposits in the desert mountain regions of western North America. It is less uniform in constitution than loess, and consists partly of wash from the mountain sides, partly of wind-borne material; but is largely the same as loess in chemical nature and possesses under irrigation a similar fertility.

Mudstone is used here as a general designation for all predominantly argillaceous sediments, whether unconsolidated as clays, or occurring in more consolidated (and usually more ancient) deposits.

Shale is the typical form of mudstone, characterized by a shaly

structure, as previously described. The word shale is sometimes used as a group name for all predominantly argillaceous deposits; but, since the word implies also a certain structure, which is not necessarily present, it is objectionable for lithological purposes as a general group name. The typical shales are formed from sandy clays in which the successive laminæ are separated by parting planes.

Pure clays commonly form massive deposits, which, when consolidated, may be cut by numerous intersecting planes into a fissile mass. Such a formation may retain no trace of original bedding planes, and therefore possess a fissile rather than a shaly structure. The position of the bedding planes may be evident by bands of color rather than by a shaly parting.

Brick clay consists of clay deposits which may be slightly sandy or ferruginous. They are ordinarily unconsolidated. When consolidated, they may give rise to true shales.

Fire clay, used for fire brick, may be siliceous, but must be free from iron oxides, lime, and potash, since these oxides tend to make the clay fusible. Fire clays commonly occur under recent swamp deposits, or under coal beds, their ancient equivalents; the soluble materials having been leached out of the clay by the waters charged with organic acids.

Novaculite or *Whetstone* is a very fine-grained sandstone of limited occurrence. According to Griswold, the Arkansas deposits are made of consolidated siliceous slimes. Rocks of this texture are frequently made, however, by the siliceous replacment of some other rock material through the action of underground waters; since it is only in rare circumstances that a sedimentary slime will occur which is not dominantly argillaceous.

CHEMICAL SEDIMENTS.

Calcareous Rocks.

Calcareous Rocks of Organic Origin.

Limestones are the most abundant of the deposits derived from material in solution; and, as previously stated, are mostly taken from solution in the ocean water by organic agency. Limestones are made upon the land to a very limited extent, and these are deposited through inorganic means. The organic

origin of the marine limestones is also somewhat complicated by the facts that the material may be subjected to considerable mechanical action by waves after the death of the organisms, and that a partial re-solution and microscopic crystallization readily takes place, cementing lime muds into rock without deep burial. These mechanical and chemical changes following the original accumulation in solid form may largely or completely destroy the evidences of organic origin. Usually, however, the rock is fossiliferous to some degree; and, according to the character of the fossils, it is known as a *shell limestone,* a *coral limestone,* a *crinoidal limestone,* or a *chalk.*

A. Coquina is a form of shell limestone in which the shells are but lightly cemented and the interspaces not yet filled with compact calcite. It forms on the beaches and shallow offshore bottoms of such coasts as those of Florida, and was there used as a building stone by the early Spanish settlers.

B. Compact Limestone may be certainly distinguished from many other rocks only by the tests of hardness and effervescence. The color may be of any shade, but is most commonly a gray-blue weathering to a buff-gray. The texture is commonly fine-grained, and a hand specimen may be of massive structure, and, to the eye, may superficially resemble a piece of compact lava.

C. Marl is (roughly) half clay and half calcium carbonate. It is only semi-consolidated, weathers readily, gives a strong earthy odor, and an equally marked reaction with acids. It is extensively used as a fertilizer. The ratio of calcium carbonate to clay may be determined by dissolving a weighed amount in acid, drying, and weighing the residue.

D. Argillaceous Limestone.— Marls may become completely consolidated, and in Europe the same name is used for such as for the unconsolidated marls. In America, however, such solid forms are known by other names, there being two chief varieties of argillaceous limestones, each with somewhat less alumina than in the typical marl. These are the following: —

E. Hydraulic Limestone or *Cement Rock,* an argillaceous limestone with about 70 per cent. of calcium carbonate. It is often somewhat slaty in appearance, frequently possesses a somewhat silky luster on fresh fracture, and may be black from the

presence of carbon. Such a rock is calcined and ground for a hydraulic cement. For such purposes it must be almost free from magnesium.

F. Lithographic Limestone is a very fine-grained, massive, somewhat argillaceous limestone, free from flaws, and offering a surface suitable for drawing or writing.

Calcareous Rocks of Inorganic Origin.

A. Cement and *Vein Calcite,* calcareous deposits of inorganic origin, are formed very widely as deposits from underground waters.

Rain waters are free from mineral matters until they meet the surface of the earth, but that portion sinking into the rocks at once begins to dissolve rock materials, chiefly the more soluble ones, giving the familiar "hardness" of underground waters. Portions of these waters may become saturated with various materials in solution. From such a saturated state some precipitation may readily take place, cementing porous materials and filling fissures. Such chemical deposits are most commonly either silica from warm or hot waters or calcite from cold ones. The two substances, however, often occur together.

B. Travertine. Calcareous Tufa.— Calcium carbonate is only slightly soluble in pure water; but, when carbon dioxide is present in excess, giving carbonated waters, the solubility is much increased, the material going into solution as the bicarbonate of lime. Upon exposure to the air, however, the excess of carbon dioxide escapes, and most of the calcium is consequently thrown down as carbonate. Evaporation also aids in the deposition. The action is especially characteristic of arid and semi-arid regions, since there evaporation is rapid, and the calcareous incrustations are not removed by the dissolving action of frequent rains. The soils of such regions not uncommonly have nodules or platy layers of travertine developed within them and known in the southwestern part of the United States as *caliche.* The waters of many calcareous springs are more or less filled with sticks, leaves, and stalks of grass, and the water trickles over and through the matted mass. The result is a spongy deposit collecting around all objects, in which, after the decay of the organic matter, molds of the organic forms

remain. This spongy deposit, from its porous nature, is called by the Italians *calcareous tufa.* It is to be distinguished from porous calcareous rocks resulting from partial solution during the process of rock decay, and also from the soft and porous igneous tuffs with which it has no relation.

Where the deposit does not collect in a spongy manner about miscellaneous objects, but on the contrary results finally in a hard and rather compact variety, it is known as *travertine.* In this form it collects in places on the surface in thick deposits, but more especially in limestone caves, where it gives rise to *stalactites* and *stalagmites,* the former pendent from the roof and resembling icicles in form, the latter appearing as incrustations and fluted and rounded pinnacles built up on the floor. Travertine is deposited in successive thin layers, usually of somewhat varying color and texture, which, when of a striking character, is known as *calcareous,* or *Mexican, onyx,* in contradistinction to true onyx, which consists of a similar deposit of silica. The two may be readily distinguished by the tests for calcite and quartz. The layers of travertine are usually made up of compact prismatic elements perpendicular to the surface of deposit.

The two names travertine and tufa are largely synonymous, but travertine is the preferable of the two, since the word tufa is used also in the sense of tuff. In so far as a distinction is drawn between the two words, travertine applies to all the more or less compact varieties of the deposit, tufa to the very porous aggregates. Tufa is therefore best used as a word describing a special variety of travertine.

C. Oolitic Limestone is readily recognized when well developed by its resemblance to a mass of fish eggs. Occasionally the spherules are as coarse as peas, and may be seen to consist of concentric shelly layers. They are observed to form in certain agitated, lime-charged waters, as in the mineral springs of Carlsbad or on the coral beaches of the Bahamas; also on the shores of Great Salt Lake. Here the water is incapable of holding lime in solution on account of the overwhelming presence of other salts and not because of special abundance of the lime. In this case it is derived from the inflowing river waters. The deposition of oolite is found to be due, at least to a considerable extent, to the presence of incrusting algæ which absorb the lime

into their tissues. It is thus partly, if not largely, of organic origin.

D. Dolomite consists of an equal number of molecules of calcium carbonate and magnesium carbonate united in molecular combination. In the rocks all gradations are found between pure limestone and pure dolomite, and such transition varieties are known as dolomitic or magnesian limestones. The characteristics of hardness and effervescence as listed in the tables, serve to distinguish limestone and dolomite. In dolomitic limestones, as noted also in the chapter on minerals, a further distinction may be observed upon weathered surfaces of the rock, the more calcareous portions dissolving more rapidly, and leaving an irregular, somewhat porous structure, but one which must be distinguished from the originally porous structure of coquina or tufa.

Magnesium is not used by organisms for skeletal purposes, so that the ocean waters are highly charged with magnesium in the forms of chloride and sulphate . In consequence, it is sometimes found, as for instance in a boring on the coral island of Funafuti, that, as the limestone muds accumulate, they react with the magnesium salts in solution, as the result of which the relatively insoluble magnesium carbonate is deposited. Underground waters carrying magnesium react in a similar manner when meeting calcium carbonates. Dolomites are thus found to have been sometimes formed over ancient sea bottoms and sometimes by reactions of subterranean waters. The first kind occur in regularly bedded deposits, the successive strata often varying largely in the magnesium content. The second kind are usually irregular in distribution, and show brecciated structures, since the transformation of calcite into dolomite results in a greater density and lessened volume.

Siliceous Rocks of Chemical Origin.

Organic.

Diatom Earth, known also as *tripoli* and *infusorial earth,* is a deposit made from the microscopic siliceous skeletons of diatoms, a group of microscopic plants living in both salt and fresh waters. In most localities, however, the sparing amount of the deposit is masked by the much larger quantity of clay or calcareous material which is intermixed. Where the other

substances are deficient, as over certain tracts of the ocean and in certain lakes, the diatomaceous deposit may be relatively pure. As noted in the table, ancient deposits may be distinguished from chalk, which they superficially resemble, by the lack of effervescence with acid.

Siliceous Sinter, known also as *geyserite,* from its typical occurrence in geysers, is a spongy form of silica, resembling in that respect calcareous tufa, but readily distinguished by its lack of effervescence. It is deposited as gelatinous silica in algæ living on the walls of certain hot springs whose waters are siliceous. Upon the death of these lowly vegetable organisms the gelatinous silica slowly loses its water of combination and gives rise to the siliceous sinter.

Inorganic.

Chert. All limestones have some silica in their constitution, derived to some extent from the decay of silicates forming the rocks of the land, as the more impalpable dusts of silica and clay are present in exceedingly minute amounts in all ocean waters from which they slowly settle and mix with the lime deposits. The silica, however, results mostly from the accumulation of the siliceous skeletons of sponges, diatoms, and radiolaria, all living in abundance in the ocean waters. It is thus originally taken from solution by organic means, and could consequently be classed as of organic origin. Where this silica is of noticeable amount in the limestone, it tends, however, to collect, by inorganic processes, into concretionary masses very different in form from the originally diffused state; and therefore the aggregates are best classified with deposits of inorganic origin. Upon the retreat of the sea and the weathering and erosion of the limestone, these remain upon the surface as hard, fine-grained, very irregular fragments, readily distinguished from the pebbles of a conglomerate. In some cases the limestone may be so full of chert that this concentrated in the soil may render it unfit for agriculture. Fragments of chert derived primarily from solution of limestone formations may be carried by streams, and rounded by contact with surrounding materials, and may thus give rise to the pebbles of conglomerate formations. The chert in this case may still be distinguished from other forms of quartz

by its compact and microscopically crystalline texture as seen upon a freshly fractured surface.

Flint is a particularly uniform and fine-grained variety which occurs as concretions in chalk formations.

Siliceous Fillings. — These originate as the fillings of porous deposits or in cracks or fissures of any sort, and arise from water solutions from two sources. First, rain waters descending into the rocks carry forward the work of rock decay, and in the process take into solution a certain small amount of silica. This may finally be precipitated through more soluble substances taking its place in the solution, or other chemical reactions, and in this way may be deposited as cement silica below the surface of weathering. It is thought to be an important aid in the consolidation of many sediments. Siliceous petrifications of fossils also arise in this way, organic acids precipitating the silica in place of the decaying tissues. Second, hot ascending waters, on nearing the surface of the earth and cooling, must deposit nearly all of their relatively large burdens of silica. This is a common origin of fissure vein quartz in regions of igneous intrusions and deposits of the valuable metals. Such vein quartz is recognized by its lack of granular character, by its frequent parallel banding, and by the frequent development of the characteristic crystalline form. The vein quartz in metamorphic rocks is often, however, minutely fractured, giving an appearance of granulation; but in that case the quartz is typically of that variety known as milky quartz, and would seldom be confused with quartz rocks of sedimentary origin.

Carbonaceous Rocks.

The carbonaceous rocks differ from the other divisions of the sediments in that they are not derived from solid igneous rocks, but from the carbon gases together with smaller proportions of the simple gases, hydrogen, nitrogen, and oxygen. At least a considerable proportion of these gases have originated, however, from the earth's interior where they are constituents of the igneous magmas. The remainder, even if derived from a primitive terrestrial atmosphere or later from cosmical sources, are still akin to the gases of igneous origin. These gases represent that fraction of magmas which remains gaseous at tempera-

tures at which the greater portion becomes solid. The carbonaceous rocks differ in another respect in that the whole of the coal deposits and probably by far the greater proportion of the petroleum deposits can originate only through the existence of organic processes. In the case of other chemical sediments organisms merely take advantage of and direct processes which would go on without them, but in the case of the coal series they are responsible for the initiation of the process — the making of vegetable tissue. While dependent thus upon the existence of life, the resultant rocks are clearly seen to fall under the chemical division of sediments and to show relationships to the limestones, quartz rocks, and iron ores of organic origin.

Coal Series.

The coal series embraces the stages from the original form of the material as woody tissue, through *peat, lignite,* and *bituminous coal,* to *anthracite coal.* Beyond this it passes by extreme metamorphism to graphite. Coaly matter exists also in all degrees of impurity with other sedimentary materials, giving rise, where abundant, to carbonaceous shales, sandstones, and limestones, black as coal in color, and able to burn with difficulty when mixed with purer forms of coal, but leaving large amounts of ash. Where carbon is present in small amounts, it serves merely as a black coloring matter in various stages of dilution, and in that condition it is common in many kinds of sedimentary formations. The necessary steps by which carbon is deposited in the rocks are as follows: —

It first appears at the surface of the earth in the form of carbon dioxide, CO_2, and as stated is apparently largely if not wholly supplied from igneous rocks. These emanations coming mostly from the molten magma but in part released by the decomposition of the solid rock, are partly in the form of carbon monoxide, CO, and hydrocarbons, chiefly light carburetted hydrogen, CH_4. As no traces of these latter gases are found in the atmosphere, however, it would seem that they pass rapidly by oxidation into the form of carbon dioxide. This in turn is not a stable component of the atmosphere, since rain water absorbs it to some degree, and in solution it combines with the rocks, destroying silicates and forming carbonates. Another

portion is absorbed directly from the atmosphere by the leaves of plants. There, by aid of the energy derived from sunlight, the carbon dioxide is broken down, the oxygen passes out of the leaves back to the atmosphere, and the carbon with oxygen and hydrogen, the constituents of water, is built up into organic substance. The vegetable kingdom, by thus decomposing carbon dioxide with the aid of the energy of sunlight, supplies atmospheric oxygen and organic matter, the two substances most essential for the existence of the animal kingdom. Recombining in the animal body, they there re-liberate the solar energy absorbed by the work of breaking up the carbon dioxide and stored up as potential energy in the plant tissues. The carbon dioxide and water, with small amounts of mineral matter, are thus seen to be the fundamental food substances of the whole organic world, — both vegetable and animal kingdoms.

The carbon which enters into vegetable and animal tissues is not in most cases permanently withdrawn from the atmosphere, but upon the death of the organism is restored to it by the oxidizing processes of decay. Where oxidation is prevented, however, as under stagnant waters, decay is very imperfect. A part of the carbon, combining with some of the hydrogen, goes off in the form of the hydrocarbon, CH_4, known in this case as marsh gas. The oxygen and hydrogen chemically combined in the woody tissue slowly separate from the remaining carbon, and the latter becomes buried and preserved beneath the accumulating mass of similar nature. Thus on each round of the carbon dioxide through the organic cycle the earth takes toll on the supply of the gas, a large amount becoming locked up as carbonates, chiefly as calcite, a smaller portion forming carbonaceous deposits. These drains upon the atmospheric supply of carbon dioxide are so great that only a trace, 0.04 per cent., remains in the atmosphere; that in solution in the ocean serving, however, as a further supply. Were it not for continuous, though more or less irregular, renewal from deep-seated sources of igneous nature, with possibly small additions from outer space, it seems certain that the present supply in the atmosphere and ocean could not last for more than a few hundred thousand years at the longest. The amount now present in the atmosphere is but an insignificant fraction of that which in past time has passed

as emanations from igneous sources through the atmosphere and into the sedimentary formations. Theoretically, some small amounts of carbon gases are supposed to be picked up by the earth in its journey through space, but there has been no demonstration that this is an adequate supply; while, on the contrary, the earth's interior is known to be an important and probably a sufficient source.

Taking up the several specific forms in which carbon occurs in the coal series the following definitions may be given: —

A. Peat. — A yellow, brown, or black aggregation of unconsolidated vegetable matter, varying from light and fibrous interwoven states to compact and clayey ones, and containing from 50 to 60 per cent. of carbon, whereas the original woody tissue contained 50 per cent. It occurs in peat bogs; and there is a gradual transition from the light yellowish or brownish yellow, fibrous aggregate slightly below the surface, to a compact black mass at greater depth, showing but few fibres and of wax-like consistency.

The only condition necessary for the accumulation of peat is that the ground shall be saturated with water throughout the year, thus preventing free oxidation. These conditions are greatly favored by continuously cool and rainy climates, and flat lands such as river deltas. An approach to either of these conditions may bring about the formation of local and limited amounts of peat; but, where the climate and geography are both favorable, peat may accumulate in great thickness over broad areas. All kinds of swamp vegetation contribute to the formation of peat.

B. Lignite, or *Brown Coal,* is a brown or black compacted mass which is easily crushed and gives a brown streak. It contains from 60 to 70 per cent. of carbon, and is formed from buried peat which is not of great geologic age and which has not been subjected to severe earth pressures. Most lignites are of Tertiary age.

Both peat and lignite, from their high content of volatile matter, are especially valuable as gas coals.

C. Bituminous Coal, Soft Coal. — A compact black mass, with streak grayish black to brown, burning with a clear flame and strong bituminous smell. This, the common form of coal,

contains on the average about 80 per cent. of carbon, a marked increase over the lignites, owing to the greater elimination of volatile matter.

D. Anthracite Coal, Hard Coal. — Harder than other coals, with a resinous to metallic luster and conchoidal fracture. Burns without smoke or flame. Occurs in limited areas where mountain-making forces have resulted in a partial metamorphism of the soft coal. The content of carbon averages about 90 per cent., owing to the almost complete elimination of volatile matter.

Petroleum Series.

This series embraces combinations of carbon with hydrogen, known as hydrocarbons, forming diversified products grading from natural gas through petroleum to asphalt. They are all inflammable substances, forming fuels of great heating power; and are thought to be chiefly the products of the decomposition of organic matter, collecting in porous rocks and prevented from escaping by surrounding impervious ones. Petroleum has no relation, however, to coal, and the popular term "coal oil" is inappropriate. The same series of products are known to be produced to some extent as emanations from igneous sources, especially in the decadent stages of igneous activity, and it is unknown at the present time to what extent the commercial supplies may be in part due to this latter mode of origin. It is thought by most geologists, however, that the occurrences over large areas are decomposition products from the organic matter in the sedimentary rocks, while certain local supplies of great volume, such as the asphalt lake of Trinidad, may possibly be of igneous origin. The different species of the petroleum series are not of sufficiently common occurrence to warrant detailed description in a work of this kind.

Iron Ores.

These have been previously considered in the chapter on minerals, under the heads of *siderite, limonite,* and *hematite.* Magnetite, an important ore of iron, originates either through igneous or metamorphic (anamorphic) activities and need not be considered under sedimentary rocks.

Evaporation Products.

The occurrence of these minerals in a rock formation is an indication of a more or less arid climate at the time of origin. Gypsum and rock salt, the two which occur to a noticeable extent in the rocks, have been previously discussed in the chapter on minerals. Alkali crusts, however, though occurring on a rather broad scale in arid regions, are not found except in the rarest instances in the rocks, and therefore they have not been previously mentioned. The alkali incrustations and impregnations consist chiefly of carbonates, with smaller amounts of sulphates and chlorides of the alkalies. They are brought to the surface and concentrated there by the prolonged evaporation of the ground water during the seasons of aridity. The alkali is not washed away by the occasional rains and floods, since the first effect of the water is to wet the ground, and in doing so it carries the alkali down with it, to be brought back to the surface by renewed evaporation. It is owing to this fact of the alkali being kept at the surface or within a few feet of the surface by capillary action and evaporation, that drinkable water may often be obtained at a depth of a hundred feet or so, even in the worst alkali regions. As sediment accumulates over river plains in arid climates, the alkali is thus continually drawn upward to the new surface, preventing the accumulation of the alkaline carbonates and sulphates in the rocks. Gypsum and rock salt are not subject to the same limitations in occurrence, since as relatively pure masses they originate especially from sea or lake waters and not on river plains, and are laid down continuously for long periods of time at the bottoms of lagoons or lakes, to be finally covered and protected from re-solution by a deposit of clay.

Chapter V.

THE METAMORPHIC (ANAMORPHIC) ROCKS.*

INTRODUCTORY STATEMENT.

As explained in the first two chapters of this work, the nature of the minerals which develop is controlled by the surrounding physical and chemical conditions. High temperature favors the formation of complex molecules in which silica is the controlling acid radical, building up minerals in which water and carbon dioxide can enter in but very limited amounts if at all. Great pressure favors the development of minerals of high density, and also tends to expel from the mineral combinations fluids or gases if the elimination of these will result in a lessened volume. Low temperatures and pressures on the other hand permit water and carbon dioxide to break up the anhydrous silicates and to enter into combination, with the result that minerals of simpler composition but aggregating greater volume are the result. Intrusions and extrusions of molten magmas occasionally permit rocks to form either near or at the surface under temperature conditions which are normal in the deeper earth but of abnormal and rapidly vanishing nature at the surface. The uplift of mountains and the resultant erosion of geologic ages also expose to the surface conditions of temperature and pressure and chemical action rocks which were formed under quite different environments. Destruction of the old rock results, and in the incoherent state the products of the rock decay are transported by surface agencies, sorted apart

* The general principles of metamorphism, the metamorphic textures and structures, the causes of metamorphism, and the principal kinds of metamorphic rocks, are rather fully treated in the Manual of the Geology of Connecticut, chap. II, by Professor Gregory. The present discussion of the subject, since it deals primarily with the lithology and not with the geological relations, cannot be as full in its treatment of causes of metamorphism, but is planned especially to give the principles of classification and the distinguishing features of the more important species.

in the process, and deposited as sediments. This completes the descensional or destructive half of the metamorphic cycle. But the very accumulation of the sediments brings the lower portions back toward the original conditions. Water of porosity is expelled. Some of that which is in chemical combination follows. Cementation takes place and the products become solid rocks. But mountain-making forces may add their enormous pressures to those already due to the weight of the sediments, and the temperatures become still higher, either owing to the work of mashing, or because of neighboring igneous intrusions. Water in consequence may be almost completely expelled, minerals of greater density may be formed, and the porosity may be reduced. Carbon dioxide is also expelled in so far as silica is present to again claim the metallic oxides. In obedience to these changed physical and chemical conditions new minerals consequently arise and a recrystallization of the whole rock results, generating schists, gneisses, quartzites, and marbles. This is the ascensional or constructive half of the metamorphic cycle. The process, however, ordinarily stops before completion, as the conditions of temperature rarely if ever become so extreme as to bodily fuse masses of sediment and turn them back once more into igneous rocks. To a very limited extent sediments may possibly be absorbed into the larger abyssal magmas but this is distinct from a bodily fusion of the masses of sediment. The cycle cannot return into itself for another reason. The sediments in their process of accumulation were subjected to a process of sorting which tends to make pure deposits of silica as sandstones, of aluminum silicate as mudstones, of lime and magnesium as carbonates, of iron as oxide ores, of potassium and especially sodium as chlorides. Although the chemical changes have never become quite complete and the sorting is never perfect, yet the sedimentary formations have become by these means so differentiated from the parent igneous rocks that even if subjected to refusion in mass the most of them could not give rise to the chemical nature of normal igneous rocks. Thus earth history does not return into itself, and with the passage of geological time the composition and also the structure of the crust become ever more complex. The rocks are consequently not to be studied merely as things by themselves, but as containing a

record of the vicissitudes through which they have passed. The recognition of the metamorphic cycle brings all the phenomena of rock change into order and shows that these changes proceed in two directions. In the one direction destructive or descensional metamorphism has been named by Van Hise katamorphism. In the other direction constructive or ascensional metamorphism has been named anamorphism. In so far as katamorphism proceeds at the surface of the earth the process and the results have been discussed under the subject of the sedimentary rocks. But the products of metamorphic changes when taking place within the earth, whether of an anamorphic or katamorphic character, are dealt with in the present chapter. They are those transformations which occur without the disintegration and final destruction of the rock mass.

THE PRINCIPLES OF CLASSIFICATION.

The classification of metamorphic rocks, like that of igneous and sedimentary rocks, can be based on two lines, one the physical conditions of pressure or temperature which have controlled the development of the rocks, the other the chemical composition, due mostly to the composition of the original rock mass, to some extent to the chemical composition of extraneous fluids which have permeated it at the time of metamorphism.

Along physical lines the metamorphic rocks may be divided into three chief groups, each group being characterized by the dominance of some one of the three following processes: dynamic, thermal, and hydrothermal metamorphism; the first where pressure is dominant, but high temperature also necessarily prevails; the others representing temperature conditions grading from those approaching the temperatures of the rock magmas to those existing at the surface of the earth.

Metamorphic rocks, as previously explained, being altered by mashing, heating, and resulting crystallization, stand as a class in some respects intermediate between those igneous rocks, on the one hand, which result from fusion deep within the earth's crust, and the sedimentary rocks, on the other hand, which result from chemical and mechanical disintegration of rocks at the earth's surface. The textures and structures in the same way stand in a somewhat intermediate relation between these two most opposed classes of rocks.

TEXTURES.

Metamorphic textures resemble those of igneous rocks in that they are all crystalline, in contrast to the clastic and amorphous textures of most of the sedimentary rocks. The prevailing textures are aphanitic, porphyritic, and phaneritic. The meaning of these terms has been given under the subject of igneous rocks.

STRUCTURES.

Metamorphic rocks may retain the structure of the igneous and sedimentary rocks from which they are formed, in case the metamorphic process has been merely one of recrystallization without mashing. More usually, however, the metamorphism has been attended with rock flowage as well as recrystallization, and characteristically metamorphic structures result. In general, there is either a banding produced by alternate layers of unlike minerals, or a parallelism of individual minerals, giving rise to a cleavage. There are several gradations in these structures which may be defined as follows: —

Slaty Structure. —(Name from its characteristic presence in slates.) Slatiness is developed by pressure sufficient to mash homogeneous rocks, and is characterized by the *capacity* of the rock to break with a relatively smooth surface on any one of a series of parallel planes. Slaty rocks are homogeneous, compact, with a felsitic texture and dull luster. The structure results from pressure, and is to be distinguished from the lamination of sedimentary rocks which it often somewhat resembles. The cleavage may or may not be parallel to the bedding planes. Slatiness should also be distinguished from the cleavage of crystals on the one hand, and from fissility on the other. The nature of mineral cleavage has been discussed previously.

Fissile Structure consists not in the *capacity* to break on a series of parallel planes, but in the *present existence* of numerous and closely parallel joint surfaces where the breaks have already been developed; so that fissility may be defined as a minute joint structure on one or two sets of parallel planes. Its development is conditioned usually on the existence of a previous cleavage, but in such cases it has come into existence later and under quite different conditions from those producing the cleav-

age, conditions which result in a fracturing rather than a mashing of the rock.

Schistose Structure. —(Name from its characteristic presence in schists, which are defined later.) Schistosity, like cleavage, implies the capacity to break upon any one of a parallel system of planes. Thus schistose rocks resemble slates in possessing a property of cleavage, but schistosity is distinguished from slatiness by the waviness or knottiness of the cleavage surface, and is developed in rocks which are more coarsely crystalline and in some cases closely banded. Schistose structure is determined by the development of minerals in parallel directions, so that the planes of cleavage of innumerable crystals are parallel, giving continuous surfaces of easy breakage. Where the minerals are segregated into planes, only the mineral having the readiest cleavage will be visible upon the splitting surface. To ascertain what other minerals are in the rock it is necessary, therefore, to examine a fracture across the cleavage.

Gneissoid Structure. —(Name from its presence in the gneisses.) Gneissoid or gneissic structure is the term applied to a banded state of the rock mass in which the adjacent layers consist of different minerals or associations of minerals, as, for instance, bands of quartz and biotite alternating with bands predominantly of feldspar. In other cases there is merely a slight tendency to parallelism in the arrangement of the minerals. The cleavage which characterizes the structures previously considered is not necessarily present in a notable degree, and the rock may therefore break diagonally across the planes of banding. The latter, however, will usually give the surfaces of easiest fracture. The structure when present is always evident in the rock mass, but may not be visible in a small portion, so that some gneisses in hand specimens would be described as possessing a massive structure. In gneissoid rocks there is not such a marked segregation and parallel development of the minerals as in the schists, and therefore more than one mineral is ordinarily visible on the plane of the gneissoid structure. There is of course a gradation between schists and gneisses. In general, however, the two structures may be separated as follows: — Schists break readily into thin plates, the cleavage plane, or foliation plane as it is generally called, controlling to a marked degree the shape of

the fragments. Gneisses do not break readily into thin and broad plates, since the foliation is less marked and less universal. An older usage which defined gneisses as feldspathic rocks and schists as rocks without feldspar, cannot be regarded as good usage since it attaches a particular chemical composition to terms which are primarily structural, though it is true in general that feldspar is more abundant in the gneisses than in the schists.

CONDITIONS OF METAMORPHISM.

Dynamic Metamorphism.

This is the result of irresistible earth movements which remold and recrystallize rocks of any origin, though operating most readily upon comparatively weak rocks. *Dynamic metamorphism* is often called *regional metamorphism,* on account of the large areas which are underlain by metamorphic rocks of dynamic origin. Dynamically metamorphosed rocks may be observed especially, — first, along the axes of those mountain chains which have been made by severe mashing and folding, the metamorphic rocks being exposed by the profound erosion of subsequent ages; and, second, in areas of extremely ancient rocks, being almost universal among rocks of Archæan age. The mode of origin of these metamorphic rocks is determined from their geological relations and from what is known of the physical nature of rock masses. They are characterized throughout by rock flowage, giving contorted structures and an absence of fracture planes. Such structures could only arise where the rock was buried to such a depth in the crust that, on account of the pressure, no fracture plane could form or remain open, but immediate re-welding of any hypothetical fissure must occur. The depth at which fracture is impossible depends upon the strength of the rock mass, the temperature, and the slowness of application of the stresses; rock flowage being favored by natural weakness, high temperatures, and slow movements. But in any case, from what is known of the physical nature of rocks, such flowage could only arise through crustal mashing at depths of a mile or more and usually several miles. Under such conditions the temperature is necessarily high in comparison with surface temperatures, since the average increase of temperature with depth is 100° F. per mile, and at times of mountain-making

the crust movements alone would serve to raise the temperature. Massive igneous intrusions, if present, would also serve to greatly increase the normal crustal temperature.

Thermal Metamorphism.

Thermal metamorphism, also called *static metamorphism,* occurs where the temperature becomes so high that the original minerals of the rock mass, especially if resulting from rock decay, while not fused, are yet no longer stable, and therefore a crystallization into new minerals is effected. The sedimentary rocks are naturally the ones most profoundly affected in this way, since their minerals were formed at surface temperatures. This process may go on over broad regions in connection with dynamic metamorphism, but occurs more especially in limited areas as the result of intrusions of igneous rock, and then gives rise to the local effects of what is known as *contact metamorphism.*

Hydrothermal Metamorphism.

Hydrothermal metamorphism originates through the action of infiltrating heated waters, which, by bringing in some substances and taking out others, change the chemical composition of a rock mass, making other minerals more stable under the particular conditions prevailing, and consequently effecting a recrystallization. Hydrothermal metamorphism, like thermal metamorphism, may sometimes operate over large areas, but is usually the most local of the three. It may occur in the upper zone of dynamic metamorphism or the outer zone of thermal metamorphism, or without the coöperation of the other processes. The minerals which arise in hydrothermal metamorphism are determined not alone by the chemical composition of the rock and the substances in solution in the infiltrating water, but also by the temperature. For instance, in close relation to a large mass of igneous rock, steam may pass in at extremely high temperatures, carrying with it materials which build new minerals, but anhydrous minerals, since at these temperatures the steam cannot enter into chemical combination. At lower temperatures, on the other hand, such as exist at greater distances from a recently intruded igneous mass, the water may itself combine with the rock, together with the materials which it brings, and result in

hydrous minerals such as chlorite, talc, and serpentine, but certain anhydrous minerals such as quartz and calcite are also of frequent occurrence. Hydrothermal rocks may originate in the outer zone of the crust, the zone of fracture, as well as in the deeper regions where dynamic metamorphism can arise. Hydrothermal metamorphism grades down on the one hand to ordinary weathering at surface temperatures and upward on the other into true thermal metamorphism. In the absence of definite knowledge as to the highest temperatures at which water may combine, the upper limit has been assumed by some at 365° C. or 690° F., the critical temperature above which water cannot exist as a fluid even under great pressures. At somewhat lower temperatures, the process is much more effective.

COMPOSITIONAL FACTORS IN CLASSIFICATION.

As in the case of igneous and sedimentary rocks, two principles of classification must be employed for those of metamorphic origin. The preceding pages have discussed the controlling conditions of a dominantly physical nature, that is, the conditions of origin of metamorphic rocks dependent upon the physical surroundings of pressure and temperature.

The second principle of classification is that depending upon the mineral nature of the rock mass, and is therefore ultimately chemical. Where the original nature of the rock, previous to its metamorphism, is known either from the specimen itself or from field studies, one may go beyond the mere chemical nature, and use the geological knowledge in the classification. Thus one may speak of a granite-gneiss, or a conglomerate-gneiss; meaning in the first case a gneiss made by the metamorphism of a granite, in the second case a gneiss made by the metamorphism of a conglomerate. In the case of metamorphic rocks this custom is frequently followed, since the mode of original formation of a rock mass is to be sought as a part of the knowledge concerning it, and the metamorphism has been only an important incident in its later history. Where the original nature and the character of the subsequent metamorphism are in any degree doubtful, they should not, as stated previously in the discussion regarding igneous rocks, be used for purposes of classification. In such cases the classification must be based on the specimen

alone, and be determined wholly by (first) chemical and consequently mineralogical characters, and (second) textural and structural characters. Such a classification is outlined in Table VI, and the following discussion of the names there given indicates to what extent one may go beyond the chemical characteristics and attribute to the names a geological meaning.

A CLASSIFICATION AND DESCRIPTION OF METAMORPHIC ROCKS.

ROCKS MADE BY DOMINANT DYNAMIC METAMORPHISM.

The rocks resulting from dynamic metamorphism may be divided into three chief groups according to the resulting structures.

The Gneisses, characterized by their gneissoid structure and usually coarsely crystalline texture, have commonly as their dominant minerals feldspar and quartz.

The Crystalline Schists are characterized by the schistose structure, and usually by a rather fine-grained crystallization. They are predominantly quartz-mica rocks, since feldspar by sufficient crushing becomes largely transformed into quartz and white mica.

The Marbles, characterized by a nearly if not quite massive structure, and by either a fine or a coarse texture, are predominantly calcite rocks, and therefore of sedimentary origin.

Gneisses.

Gneisses are characterized by the somewhat banded or imperfectly foliated structure previously defined as gneissoid. As this is usually produced by only moderate mashing of the rock, the original nature of the formation is frequently evident, either from the mineral composition or from field studies. Quartz, feldspar, and mica are the minerals most commonly present; but the word gneiss, as here defined, in conformity with the present usage of many petrographers, is given entirely a structural and not a mineralogical significance. The character and origin of gneisses gives rise to the threefold division shown in the table.

Gneisses Derived from Igneous Rocks. — These may be recognized by their close resemblance to the parent igneous

rocks, the metamorphism having been only sufficient to produce the gneissoid structure. Where a more thorough mashing and recrystallization has taken place, the rock may still often be traced into a region where the igneous origin is evident. Gneisses of igneous origin may be further subdivided into species, according to the kind of igneous rock from which they have been derived. If the derivation is evident, the term *granite-gneiss* is used to indicate a rock derived from a granite, *syenite-gneiss* from syenite, and so on. Some igneous gneisses owe the structure to the original mode of intrusion and crystallization, rather than to later mashing.

Gneisses Derived from Sedimentary Rocks. — These may frequently be distinguished upon careful examination, either in the laboratory or the field, by the detection of the remains of sedimentary structures or textures, such as bedding planes, fossils, or pebbles not fully obliterated, and also by the composition, quartz being usually the dominant mineral, feldspar being also present, with possibly some carbon and considerable mica. It was seen from the discussions upon sedimentary rocks that sodium is largely extracted from the sediments during the process of rock decay, and concentrated in the sea; so that rocks of sedimentary origin are notably poor in sodium. The lime and magnesia, on account of their relative solubility, are also largely removed; but magnesia less so than lime; with the result that the mechanical sediments are characterized by the abundance of quartz and aluminous minerals.

Where a sedimentary origin can be proved, such terms may be used as *conglomerate-gneiss* or *quartzite-gneiss,* according to the kind of rock from which the gneiss has been derived.

Gneisses of Unknown Origin. — These are the gneisses in which dynamic metamorphism has gone so far that the nature of the original formation can no longer be traced. If our knowledge were derived solely from hand specimens, many gneisses would have to be placed in this class: where such knowledge can be supplemented by expert geological and chemical investigation, the origin of most gneisses is determinable. Certain gneisses in this group are indeed of mixed igneous and sedimentary origin; since, in connection with the dynamic metamorphism of sedimentary rocks, igneous injections

throughout the mass may occur. The result is that the proportion of igneous and sedimentary materials is variable from one specimen to another, and is indeterminable. In all cases where the original nature of the formation is in doubt, the rock should simply be called a gneiss. The name may be further qualified, however, according to the minerals present. If these are the same minerals as would form a granite, the rock may be known as a *granitic gneiss;* if they are the same minerals which would form a syenite, it may be known as a *syenitic gneiss;* in contrast to *granite-gneiss* and *syenite-gneiss* which are of evident igneous origin. Where one mineral is dominant in the gneiss, the name of that mineral may be used to qualify the rock, as, for instance, *hornblende gneiss* or *quartz gneiss;* but, where several minerals are abundant, the practice which is sometimes employed of stringing together the several mineral names is awkward though permissible. Such a method, however, has the advantage of not inviting guesses in regard to origin, and prevents the possible confusion of somewhat similar terms, as granite-gneiss and granitic gneiss.

Crystalline Schists.

These are characterized by the schistose structure previously defined, and show various degrees of metamorphism from rocks which may have been originally stratified or massive, and which were usually fine-grained, into highly modified foliated rocks.

Slate, the form showing the slightest degree of metamorphism, is the first to be considered. Slate is characterized by a microscopic texture and dull, stony luster, combined with smoothness and perfection of the rock cleavage. The cleavage, as discussed in all text-books of geology, is held to be due in the majority of cases, either to a flattening of all the particles or to their rotation into one plane through a mashing of the rock mass, or, more important still, to a parallel growth of new minerals. The resulting flatness and parallelism of the particles cause a cleavage at right angles to the pressure. The slaty cleavage may be called a *flow cleavage. Fracture cleavage* is a condition which may much resemble the other, but is due to a sliding of adjacent laminæ with respect to each other with the development of cleavage between, and is a phase of fissility, a topic

previously discussed. Slates, developed in all cases by crustal forces acting upon a previously consolidated mass, should be sharply distinguished from shales, which they somewhat resemble in appearance, but with which they are strongly contrasted in mode of origin. Shales with smooth bedding planes and well developed bedding cleavage may, however, strongly resemble true slates, and are often popularly known as slates, so that the word is used in both a common and a scientific sense. The slates are characterized by a pressure cleavage which has no necessary relation to the direction of the bedding planes, and they may often be distinguished from shales by noting the passage of the stratigraphic bands through the rock mass at an angle to the cleavage; so that on a cleavage surface they are seen as parallel "ribbons" of slightly different color crossing the face of the slate. Where the layers of the original rock differed little in composition and consequently in color and general aspect, a pressure cleavage may be undistinguishable from a smooth bedding cleavage. Usually, however, the geological relations will readily indicate the true character. On the average, the slates are denser than the shales, and they give a pronounced ring upon tapping with the hammer, and show a smoother and more uniformly developed cleavage.

Phyllite. — Phyllites are distinguished from slates by a somewhat greater degree of metamorphism, especially a slight degree of thermal metamorphism, resulting in a more lustrous and silky texture of the cleavage surface, which is, furthermore, often somewhat wavy or lumpy in character. The phyllites form an intermediate group between slates and mica schists. By some geologists the name is little used, and the group of phyllites is broken up, the less crystalline and more smoothly cleavable being classed as slates, the more lustrous and wavy as schists. The gap between typical slates and typical mica schists is however so wide that the employment of another name for intermediate forms seems desirable.

Mica Schists are made by regional metamorphism, involving both dynamic and thermal metamorphism, and from any kind of rock, provided the mashing is sufficiently marked. They are most commonly, however, the metamorphic equivalents of the argillaceous sediments, and the two most abundant minerals are

quartz and mica. They are characterized by the schistose cleavage as previously defined. The rock is thoroughly crystalline, and may be distinguished from phyllite by the coarser visible crystallization and more irregular cleavage; the latter curving about the larger crystals or crumpled by oblique pressures. Slate, phyllite, and mica schist, therefore, represent three stages in the metamorphism of fine-grained rocks.

Quartz Schist. — Made from the mashing of sandstones which were relatively free from clay, so that mica in conspicuous quantity was unable to form. Quartz, consequently, makes up by far the greater portion of the rock mass. What little mica is present is developed on the cleavage planes, so that a view of a cleavage surface may give a false idea in regard to the abundance of mica. A view of the fractured end is, therefore, necessary in order to obtain a correct idea in regard to the mineral composition of the rock.

Hornblende Schist. — Where rocks rich in lime, iron, and magnesia have been greatly altered by metamorphism, hornblende schists result. The hornblende forms black or green-black matted surfaces, the small prismatic crystals lying with their axes roughly parallel or at least in the same plane, indicating the direction of compression at right angles to the cleavage. They may be distinguished from mica schists by the hardness of the rock, the felt-like appearance of the surface, and the usually feebler luster. They are made most commonly from gabbros, igneous rocks which solidified deep in the crust, and therefore in situations favorable for later dynamic metamorphism. Diorite dikes forming offshoots from granite masses are also often mashed into hornblende schists. Igneous rocks of abyssal origin are frequently subjected to dynamic metamorphism, since they do not require a preliminary burial as do surface deposits, but merely a later profound erosion in order to expose them to observation at the surface. They are, however, more resistant to mashing forces than are the argillaceous sedimentary rocks. Hornblende schists may be made also from sedimentary rocks of suitable composition, a calcareous, ferruginous, and aluminous sandstone being the most favorable.

Amphibolite is an almost synonymous term, but is more inclusive since it comprises schistose or gneissoid rocks holding abun-

dantly any mineral of the amphibole group. Amphibolites may be more or less foliated dikes, or they may comprise large quantities of rocks of sedimentary or partly sedimentary origin. Such rocks are as commonly green as black.

Various Minor Schists. These are kinds which are distinguished from the preceding species by the presence of one or more of the *minerals characteristic of the metamorphic rocks* given in Table III. Such schists are usually varieties of mica schist, and usually of sedimentary origin. They may be divided into two classes not sharply distinct.

First, those characterized by minerals due to extreme dynamic and thermal metamorphism, rather than by those which indicate an unusual chemical composition of the original rock. They are named according to the accessory minerals which are present, giving rise to such names as *garnetiferous mica schist, andalusite schist, cyanite schist,* and *staurolite schist.*

Second, those due to an original peculiarity in chemical composition, producing upon dynamic metamorphism such products as *graphite schist,* from the metamorphism of carbonaceous deposits; *actinolite schist,* from originally siliceous and ferruginous rocks; *hematite* or *magnetite schist,* from purer deposits of iron ore.

Marbles.

Marble is the result of the metamorphism of limestone. If the latter is dolomitic, a dolomitic marble is the result. The texture may be fine or coarse, but must be wholly crystalline, and, as a result, a fresh fracture presents the appearance of loaf sugar, and the cleavage planes of the innumerable grains of calcite give a sparkling effect when viewed in the sunlight.

Pure limestones or dolomites assume a schistose structure with great difficulty. This is because the calcite grains possess three equal cleavages inclined at 75 degrees to each other, and, since each unit crystal tends to maintain the form of a cleavage fragment, they cannot develop into prismatic or flat crystals upon pressure. On the contrary, the easy yielding on cleavage planes, and the ready recrystallization of calcite in the presence of heat and pressure, tend to preserve a granular crystalline texture and a massive structure even in cases of extreme rock mashing. If the marble be impure, however, various minerals may result upon

metamorphism, and these being flattened and recrystallized in parallel position upon the mashing of the rock mass may give rise to a banded structure. Serpentine and mica are two of the most common minerals which form in this way, the first from siliceous dolomitic limestones, and the second from those of an argillaceous nature. Among the chief varieties of marbles may be mentioned the following: —

Serpentine Marble is mottled green and white, and when regular in pattern is very beautiful.

Ferruginous Marbles are colored buff or red by the presence of iron oxide.

Brecciated Marbles are those which have been shattered by crustal movements at a time when the rock was not so deeply buried as to be in the zone of flowage, and therefore yielded by fracture. Recementation of calcite rocks takes place readily, and, since the cement is generally of a different color from the fragments, very handsome effects may be produced. Ornamental marbles thus arise from various impure and brecciated forms.

The colors of marbles are generally brighter than those of the unmetamorphic limestones from which they were produced, and from an ordinary pure limestone of grayish or bluish color a snow-white massive marble will result.

ROCKS MADE BY DOMINANT THERMAL METAMORPHISM.

Silica Rocks.

Quartzites are massive, compact quartz rocks, in which the original bedding may be preserved, but, unlike the sandstones from which they were derived, they are so slightly porous that almost no water can be absorbed. The siliceous cementation by which the pore space of the original rock is almost obliterated, is accomplished by a growth and interlocking of the originally rounded sand grains, so that a *fracture surface passes through, and not around, the individual grains,* giving a compact and even texture with a slightly splintery fracture suggesting that of a broken piece of maple sugar. The fabric of interlocking grains which forms the rock prevents, on the other hand, the development of a clear, glassy fracture such as is found in massive quartz veins. Where a vein quartz has been crushed by earth pressures, however, and then recemented into a compact mass, a granulated

rock results which may approach a quartzite rather closely in appearance, but may usually be distinguished by the larger grains showing brecciated outlines and a clearer, smoother fracture. Quartzites are most commonly light gray, buff, or pink in color. Crushed vein quartz is more commonly either whiter or more transparent.

The loss of pore space in the metamorphism of a sandstone to a quartzite does not require the rock mashing due to dynamic metamorphism, by which sandstones are transformed into quartz schists; but may be attained under the pressure which is found at a depth of a few thousand feet in the earth where the temperature is high enough to promote partial solution and recrystallization of the silica. In that case it is the molecules under strain from the pressure at the points of contact of the sand grains which are dissolved most readily, and redeposited in the interspaces free from strain, thus finally leading to the obliteration of the pore spaces.

On account of the resistance of quartzose rock to mashing, quartzites are much more common than quartz schists. Where there are slight amounts of impurities in the rock the original variations from one stratum to another may lead to a distinct banded appearance, especially if the impurities are ferruginous and hence give rise to dark minerals. Thus biotite quartzite gneisses arise or other varieties dependent upon the minerals developed.

Silica-Alumina Rocks.

A *Hornfels* is an ancient mud which, after burial and consolidation into shale, has been invaded by igneous masses, but without the attendant mashing which would have transformed it into schist. As shales, unlike the sandstones, are weak rocks and easily mashed, hornfels is rare as compared with schist. Rocks of this type are dense and fine-grained, possessing a microscopic texture and resembling chert in appearance. They occur, however, in greater local volume than chert, and have originated in an entirely different way, being closely associated with igneous rocks. The name hornstone, which is etymologically the English equivalent of the German word hornfels, is sometimes applied to the rocks now under consideration, but its use in that sense is objectionable, as it is by writers in

English commonly applied to a concretionary variety of quartz essentially similar to chert and flint. True hornfels possesses a hardness about equal to that of feldspar, while chert or hornstone on the contrary, consisting of pure silica, is clearly harder. The width of the hornfels zone surrounding the igneous mass may be a few feet or a few hundred feet, depending upon the metamorphosing power of the intrusive; and in the transition to the unaffected sediments the hornfels ordinarily passes into a zone of spotted slates or schists.

Lime-Magnesia Rocks.

The *marbles* of this group, when pure, differ in no way from those produced by dynamic metamorphism; but, in the vicinity of a magma, marble, on account of its ready reaction with magmatic emanations, is apt in metalliferous regions to hold irregular masses of ores of copper, silver, or other metals, or, more commonly, masses of quartz and other valueless minerals. The absence of metamorphic structures in adjacent rocks, the presence of igneous masses, and the comparative lack of relation of the replacement minerals to the bedding planes, will serve to distinguish such marbles from those of dynamic origin. In the hand specimen such relations are of course not ordinarily observable, and then the rock is to be called a marble without qualifications which involve inferences as to the particular mode of metamorphic origin.

Iron Ores.

Hematite and *Magnetite*. — The processes of dehydration and cementation which, in the course of long periods of time, consolidate sediments into rocks, are often sufficient without actual metamorphism to transform limonite into hematite. The latter, however, in that case is typically red and earthy. Some degree of thermal metamorphism is a potent factor in hastening and completing the transformation, and especially in crystallizing the resulting hematite. Where the mashing due to dynamic action also occurs, the hematite may pass into the micaceous form of black brilliant scales resembling mica in appearance, but of course with no real mineralogical relationship.

If any deoxidizing influences are present, magnetite may result, though many magnetites in the metamorphic rocks are

of igneous origin, being ferruginous segregations from basic magmas. The particular mode of origin can of course be determined, if at all, only by expert field studies.

Mixed Types.

There are local rocks sometimes developed from contact metamorphism which do not belong clearly to any of the preceding types, and which must be named from some dominant mineral. Their mixed chemical nature may be due to derivation from an originally unsorted mass of sediments, or to additions of silica or metallic oxides carried in by the magmatic emanations. Impure limestones are especially liable to give rise to such types, and result in garnet rocks, tremolite rocks, and various others, characterized by the presence of minerals not given in the tables of this Bulletin.

ROCKS MADE BY DOMINANT HYDROTHERMAL METAMORPHISM.

Anhydrous Rocks.

Quartzite. — Where the temperature of circulating waters is sufficiently low, hydrous minerals may result unless the oxide of silicon is alone deposited. In this case it most commonly occurs not in the hydrous form, as opal; but in the anhydrous form, as quartz. Such circulating waters if hot may carry considerable silica in solution, and result in the cementation of a sandstone which would otherwise have retained its porosity, or result in the more or less extensive replacement of another rock mass by silica, usually giving in this case the smooth grain of a jasper. Such infiltration quartzites and replacement quartzites or jaspers may be undistinguishable, except by a careful study of the geological relations, from those quartzites and hornfelses resulting from thermal metamorphism. They would usually be of more limited occurrence and more irregular boundaries than the latter, since they are determined by the limits of the circulating hot waters. Quartzites may thus arise from several rather distinct metamorphic processes; and the problem of their origin can in most cases be solved only by detailed field studies, seldom by hand specimens.

Hydrous Rocks.

Introductory Statement. — The processes of weathering at the surface of the earth, although not commonly recognized in the text-books as processes of metamorphism, constitute in reality one class of metamorphic actions, those of *hydrous metamorphism;* since it is only through the presence of water that oxidation, carbonation, and hydration of surface rocks can take place. Such metamorphic products, however, as result from surface decay are very different from those formed deeper within the crust and at a higher temperature by processes of *hydrothermal metamorphism.* The formation of the surface products can only extend to a very limited depth, and they can never remain in place except as a comparatively thin mantle of residual earth, which in certain localities may attain exceptionally a thickness of one, two, or three hundred feet. On the other hand, over considerable areas formations of chlorite, talc, and serpentine rocks are occasionally found to extend from the surface to a great but unknown depth. While the hydrous nature of these minerals clearly indicates that they have not originated in a zone of true dynamic or thermal metamorphism, their uniform character to a great depth, their lack of oxidation, and the usual presence of structures indicative of rock mashing, indicate with equal clearness that they have not originated through simple hydrous metamorphism, better known as surface weathering; but have been exposed to observation by the erosion of a former cover at least some thousands of feet in thickness. Such formations appear to have originated in an intermediate zone, where pressure was exerted to a considerable extent, and where water permeated and passed through the rock in considerable amount. Considering the present depth of such formations and the amount of material which has been removed by erosion, it is seen that the temperature must have been moderately high, presumably above 100° C., though certainly not approaching the temperature of 365° C., at which point water ceases to be liquid even under the greatest pressures, and no decidedly hydrous minerals can form. It is this intermediate zone which is the region of *hydrothermal metamorphism,* distinct from the zone of thermal metamorphism below, and that of hydrous metamorphism above in the belt of surficial weather-

ing. In the presence of igneous masses it will be found beyond the zone of true contact metamorphism (thermal metamorphism), and in the presence of soft rocks it may be associated also with dynamic metamorphism.

Chlorite, Serpentine, and *Talc Rocks.* — It appears to be especially under conditions of hydrothermal metamorphism that chlorite and talc schists and the massive serpentine rocks originate. Slight differences in the chemical composition of the rock masses result in the occurrence of one or another of these species, which also frequently exist together. The silica content of these three alteration minerals is shown in the following partial analyses: —

	Silica	*Bases*	*Water*
Chlorite group,	25-33	54-63	11-14
Serpentine,	44	43	13
Talc,	63	32	5

Disregarding the water absorbed in hydration, and taking the ratio of the silica to the bases, we may see that serpentine has practically the same ratio as the iron-magnesium minerals from which it comes; talc shows a higher, chlorite a lower, ratio of silica to bases. The production of chlorite from ferromagnesian minerals thus sets free silica in the same manner as the production of kaolinite from feldspar. Chlorite schists, partly in consequence of this, are often found to include lenses of segregated quartz, and to be cut by seams and veins of quartz. The line of the original minerals cannot enter into chlorite, serpentine, and talc, and may combine with carbon dioxide to form calcite, diffused through the rock or segregated in local fissures. These hydrous schists may originate from various kinds of rocks, but those consisting of chlorite and serpentine are especially apt to come from basic igneous rocks. The chlorite schists often give evidence also of extreme mashing. The transformation of a strong and massive diabase or gabbro to a soft, green, and closely foliated chlorite schist is one of the most striking examples of dynamic as well as hydrothermal metamorphism.

Such a mashing with development of schistosity would be possible only with rocks buried at least to a depth of some

thousands of feet, in the presence of abundant water; but water of surface origin is mostly confined to rocks near the surface. Consequently the intimate and complete permeation of a deep-seated rock mass with water sufficient to permit of the hydration may in many instances be due to magmatic waters emanating from still deeper-seated invasions of magmas and saturating the rocks above, rather than to downward soaking rain waters. A conclusion as to the particular origin of the water and the cause of the hydrothermal metamorphism in individual cases may be reached, however, only by a general study of the geological relations of the formation; and even then may be a matter for suspended judgment rather than of proof.

PART II

Descriptions of the Connecticut Educational Series of Rocks

BY

GERALD FRANCIS LOUGHLIN

Descriptions of the Connecticut Educational Series of Rocks.

INTRODUCTION.

The logical development of the subject of lithology requires that the igneous rocks, the class from which all others have been derived, be treated first — a method which has been followed in Part I. In the study of rock specimens, however, it seems best to begin with the simplest class of rocks, the sedimentary, especially as these are made through the operation of processes open to observation by all. The method of procedure followed in describing the examples of Connecticut rocks has been, therefore, to take up first the untransported materials, kaolin and limonite; then the transported but unconsolidated material; next the consolidated sediments. Following these divisions of the sedimentary series come the descriptions of the igneous rocks, the metamorphic rocks, and, finally, the pegmatites and veinstones.

As a result of the limitation of the collection to the rocks of a single small state, it will be noticed in the following descriptions that certain specimens are not altogether typical representatives of their class. Thus, in the first example, the kaolin is exceptional in being derived from a feldspathic quartzite, and not from a highly feldspathic igneous rock or a clay formation. Again, the only sandstone in the state is of an unusual composition in that it is more or less feldspathic, constituting an arkose. The fact that Connecticut lies in a region which in earlier geological ages suffered repeatedly from mountain-making movements results further in a great predominance of metamorphic formations, including many rocks whose history has been exceedingly complicated. The lithology of such a province is consequently more difficult to study than that of one which contains only rocks of

sedimentary, or sedimentary and igneous origin. However, in the following pages, the attempt has been made to convey the ideas as far as possible without the use of technical terms, though these are often inserted parenthetically for readers who may wish to pursue the study of rocks beyond the immediate scope of this Bulletin.

Chapter I.

RECENT AND PLEISTOCENE FORMATIONS.

RESIDUAL MATERIALS.

The effects of rain-water, carbon dioxide in the air, and other destructive agencies, discussed more fully in Chapters I and II of Part I, are gradually to break rocks into fragments, and to eliminate by solution certain of the constituents, leaving the remainder as a residue or residual material. All rocks or rock-making minerals are composed principally of the following constituents: silica, alumina, iron oxides, magnesia, lime, soda, and potash. Of these, silica, alumina, and the red oxide of iron (ferric oxide) are not dissolved by water and carbon dioxide; the other constituents are so dissolved. Thus, if one of the minerals of a rock is a compound of potash, alumina, and silica (orthoclase), the potash will be dissolved, while the alumina and silica are left as a residual material or residual soil. If the rock contains quartz and mica besides orthoclase, the quartz also will remain as part of the residual material. The mica will be decomposed, leaving alumina and silica, and iron oxide if any is present in it. There are two iron oxides: one, the red (ferric) oxide, is not dissolved; the other, the black (ferrous) oxide, is dissolved rather readily, but usually takes on more oxygen from the air, becomes converted into the insoluble red oxide, and is left with the residual material.

But the residual material is not wholly unaffected. When alumina and silica are left by the decomposition of a single mineral, such as orthoclase, they unite with a certain amount of water and form the mineral kaolin. Similarly, the red oxide of iron unites with water, and becomes the mineral limonite. Quartz is practically unaffected by decomposing agents, and remains as loose grains in the kaolin and limonite. Other residual materials occur in nature, but the three materials above named are the only important ones in connection with the study of rocks.

No. 1. Kaolin.

Sharon, Conn.

Kaolin is a hydrous silicate of alumina, and is formed chiefly by the decomposition of feldspar. It occurs in the form of white clay. All clays are made up of kaolin mixed with fine particles of other minerals, which are called impurities in the clay. The color of clay varies with the percentage of iron. Kaolin free from iron is white, but becomes yellow to deep brown on the addition of ferric oxide. Thus, white kaolin, such as is used in manufacture of porcelain, must be derived from rocks rich in feldspar but practically free from iron. The most common rock of this kind is pegmatite, consisting of large crystals of feldspar and quartz, with a subordinate amount of mica and other minerals; but the kaolin now to be described is derived from a quartzite rich in feldspar. The word kaolin comes from the Chinese *Kauling,** meaning high ridge, the name of a hill near Jauchau Fu, where the material is obtained. The Sharon kaolin is mined at the summit of a hill over 1,200 feet above sea-level, about two miles and a half northwest of West Cornwall village. Its exact dimensions are not known, but its linear extent is thought to be at least 1,000 feet; while boring with a wash drill shows it to have a thickness of over a hundred feet. It appears to form an arch, or anticline, its sides dipping east and west and its crest sloping or "pitching" gently to the southward. It is overlain and underlain by the hard Poughquag quartzite (No. 31).

The kaolin before being dug has all the appearance of the original quartzite, and shows numerous quartz grains which have not been decomposed. Owing to the crumbling nature of the kaolin when dry, its structure cannot be preserved in specimens, although it was very clear when they were collected. Examination of the crumbled material will show its grittiness, which is due to the abundance of fine quartz grains.

The kaolin bed was formerly solid rock, consisting of quartz with a large percentage of feldspar, while the beds of rock above and below it contained only quartz with little or no feldspar. The whole formation was deeply buried beneath the surface. At some period the whole region was subjected to pressure so great as

* Dana's Text-book of Mineralogy, new edition, 1900, p. 481.

to fold and fracture the rock. Later, erosion gradually wore down the surface of land until the rock in question was exposed. Rain-water, falling upon this rock, worked its way downward through the many fractures, and converted the feldspar to kaolin, but had no effect on the quartz. Thus the bed containing the high percentage of feldspar has been converted into a mass of kaolin and quartz, but retains its original appearance and relations to the adjacent beds of solid quartz.

Residual material is not commonly found in glaciated regions like Connecticut, as practically all the soft material at the surface was scoured off by the great glacier that recently advanced over the northern part of the continent. At this particular spot, however, the kaolin was protected by lying in a sag in the top of a hill and by being partly overlain by the solid quartz rock.

This kaolin is now being mined by a wash-drill, which forces a stream of water down through a vertical pipe and washes the kaolin up again to the surface. After reaching the surface, the water, with the kaolin, is passed through two tanks in which the quartz grains settle out, while the washed kaolin, which analysis has shown to be 99% pure, settles in a third tank. It is finally taken from this and dried in a filter press, and when thoroughly dry is ready for shipment to manufactories of porcelain.

No. 2. Limonite.

Ore Hill, Salisbury, Conn.

Limonite is the hydrous oxide of iron ($2Fe_2O_3.3H_2O$) and is formed by the weathering of other minerals containing iron. It produces a rusty staining on rock surfaces; and has in such cases been derived from the alteration of certain minerals present, such as black mica or hornblende in a granite, mica or garnet in a schist, siderite (iron carbonate) in certain impure limestones. It frequently results from the oxidation of pyrite (fools' gold) either in large masses or in small grains which may be present in all kinds of rocks. Magnetite may also yield limonite, but is less readily altered than the above named minerals.

If a rock (for example a granite) originally contains only a very small percentage of iron, and a large amount of feldspar and quartz, its decomposition will yield kaolin and more or less quartz stained by limonite; but, if the rock affords little or no

kaolin and quartz, even a rather low percentage of iron in the original rock will gradually accumulate until sufficient in amount to be worked as an ore. In the eastern United States limonite in commercial quantity has been derived from large veins of pyrite, and from impure limestone strata containing iron carbonate.

Besides accumulating in this way as a residue, limonite is also derived from the oxidation of ferrous iron salts in the water of ponds, and forms the so-called "bog iron ore." This mode of origin, though unimportant commercially, brings out the significance of the name, limonite, which is derived from the Greek for meadow.

The limonite of Ore Hill, Salisbury, belongs to the residual type, and is one of many such deposits which occur in western New England and southward along the Appalachian region to Alabama. The New England deposits lie in limestone areas, and are derived from the decomposition of the limestone. The Ore Hill deposit marks the former position of a thick limestone bed lying within the Berkshire schist.

The limonite varies greatly in character, but care was taken in the selection of specimens to illustrate the important features. The mineral may be compact or earthy, and vary in color from yellow or brown to reddish; or it may consist of a mass of parallel fibers. The surface of such masses is at right angles to the fibers and appears black and highly polished. The compact or earthy portion consists of the residual limonite together with any other insoluble impurities that may have existed in the limestone, and frequently contains fine disseminated flakes of mica. These mica flakes show the close relation of the limestone to the enclosing schist, since they are doubtless derived from the original rock. The fibrous portions occur around pockets or cavities in the ore. These cavities vary in diameter from a fraction of an inch to more than a yard. The deposition of this fibrous limonite must have begun along the crevices or joints which divided the limestone into numerous blocks, while the limestone at the same time began gradually to dissolve away. Thus, as the limestone blocks became smaller, the limonite built out closely compacted fibrous masses to replace them. Gradual replacement continued so long as any iron was available. After

deposition of limonite had ceased, solution of the limestone blocks continued, until today most of them have entirely disappeared, though a few small remnants may still be found within masses of fibrous limonite.

Little remains to be said concerning the origin of the ore. In the first place there existed the bed of ferruginous limestone within the schist. When the rocks were subjected to compression and became fractured, the fractures allowed free circulation of water from rains, which gradually dissolved the limestone and oxidized the iron to limonite. The accumulation of the limonite is still going on, but, like most geological processes, is extremely slow.

Limonite is an ore of iron, and to-day constitutes about 12 per cent of the iron ore produced in the United States. The Salisbury ore is used especially for the manufacture of car wheels, and is smelted at Lime Rock and East Canaan, Conn. The fact that it can be worked in competition with the great iron ore deposits of other regions, and in spite of the absence of coal, is accounted for by the appreciable portion of hydrous manganese oxide which this ore contains. The manganese forms an alloy with the iron which in the castings gives it great toughness, a quality most necessary in car wheels.

TRANSPORTED MATERIALS.

Residual material does not usually stay long in place, since it is eroded on the upper surface and renewed from below. Wind, water, and ice are the agents of removal, transportation, and deposition; and the general result of their activities is to reduce the particles they act upon to smaller sizes, and in greater or less degree to sort the various materials. Each agent, wind, water, or ice, furthermore leaves its distinctive impress upon the earthy matter which it carries. There thus arise many kinds of transported materials, which it is necessary to understand before studying their consolidated equivalents, the older sedimentary rocks.

No. 3. Till.

Westville, New Haven, Conn.

Till is a heterogeneous mixture of bowlders, pebbles, sand, and clay, which covers the greater part of the surface of New

England. It has resulted from the grinding of rock fragments, both fresh and altered, beneath a vast glacier which transported the material in the direction of its movement, and deposited it in masses of varying thickness over the rock surface. Till has no definite structure. Bowlders of varying size are sometimes numerous, sometimes scarce; but, as many street and railway cuts demonstrate, large irregular pebbles or small bowlders are almost everywhere abundant in the till of New England. The composition of till varies according to the rocks from which it has been derived; thus till found in the Highlands of Connecticut is composed almost wholly of material derived from granite and metamorphic rocks, while till found in the Central Lowland consists largely of trap and sandstone fragments in a matrix of clayey sand. Till in the Central Lowland often has a brown or reddish color similar to the color of the brown or red sandstone from which it was chiefly derived.

Till is sometimes so firmly compacted as to require blasting when dug, but specimens taken close to the surface are usually soft and earthy. The name "till" is of Scotch origin, and is a synonym for hard-pan, bowlder clay, and ground moraine. The last two names only are significant, bowlder clay meaning clay full of bowlders, and ground moraine being the heterogeneous deposit formed *beneath* the glacier during its advance, in distinction from lateral and terminal moraines formed respectively along the sides and at the ends of glaciers. The specimen consists principally of fine and coarse sand mixed with clay and numerous pebbles. The larger pebbles are mostly diabase, or trap rock, derived from trap ridges. Fewer sandstone or shale pebbles are found, as these rocks offered less resistance to the grinding action of the glacier and were largely reduced to sand and clay. Pebbles of quartz and metamorphic rocks derived from the Highlands are also present. Till some distance below the surface usually has a bluish color, but is changed near the surface, as the specimen shows, to yellow, owing to oxidation of the iron present. Before the advance of the continental glacier the ground surface consisted of soil derived directly from decomposition of rocks. Rock appeared at the surface in jagged, weathered ledges on the hills, but was buried beneath its own decomposition products in the lower places. The advancing

glacier scraped off all the soil, and ground the underlying rock surface, until all the altered rock was carried away and a part even of the fresh rock, especially on the hills, was removed. Bowlders were plucked from the more elevated ledges, and carried onward with the decomposed and fresh rock powder, either under or within the ice.

In time the glacier margin came to rest, and finally the whole melted away, leaving the accumulation of till as it appears to-day. Wherever recent removal of the till reveals the underlying rock, the latter is unaltered, and shows a smooth, almost polished surface, with frequent parallel scratches or "glacial striæ." Both the smooth surface and the striæ were produced by the grinding of the moving till against the rock, and the direction of the striæ indicates the direction in which the ice advanced.

Till has practically no economic value in New England. Attempts have been made to manufacture brick from it, but the necessity of eliminating the numerous pebbles and bowlders prevented success, especially since clays formed in glacial lakes (Specimen No. 7) were so abundant.

No. 4. Glaciated Pebble.

Westville, New Haven, Conn.

This glaciated pebble represents the type found in till. The size of the specimens is below the average, as only small ones are suitable for a cabinet collection; but, although the size may vary from small pebbles to bowlders several tons in weight, the character is always the same. Two opposite sides of the pebble are polished and nearly flat, while the remaining surface is irregular, with somewhat worn edges and corners, giving the typical *subangular* character. In many instances, the flattened surfaces are crossed by parallel scratches or grooves (striæ); but this is by no means universal. Glaciated pebbles may be formed from any kind of rock, but the best examples come from the harder kinds, as unweathered trap, fine granite, and quartz. The softness and relatively loose texture of sandstone and shale, especially of the latter, prevents good examples from these rocks; and, owing to their tendency to weather

rapidly, the polished surfaces of exposed pebbles are soon destroyed.

These polished surfaces and striations, as was mentioned under *till,* have resulted from the grinding action of the ice sheet. Fine and coarse materials were dragged along together between the ice and the rock surface. The fine material, rubbing over the surfaces of the pebbles and bowlders, gradually polished and flattened them; or the under surface of a pebble may have been ground by friction against the bed rock. Where an exceptionally hard or sharp grain came into contact with the smoothed surface, it cut deeper and formed a groove; or the effect may have been produced by a sharp corner of one pebble scraping along the flattened surface of another. The flattened surfaces obviously must have lain parallel to the surface of the ground, or normal to the downward pressure of the ice. Thus, a pebble of any shape whatever, by sliding slowly along, developes a flattened top and bottom, while its sides, receiving less pressure, suffer little abrasion and retain their irregular form.

No. 5. River Gravel, Glacial Period.

Westville, New Haven, Conn.

River gravel is gravel deposited in river beds, in distinction from lacustrine and marine gravels, deposited, respectively, in lakes or along ocean margins. It consists of pebbles embedded in a matrix of sand derived from any or every kind of rock which lies within the drainage basin of a river system; but the pebbles of the harder rocks — granite, trap, quartzite, and gneiss — are predominant, while those of the softer rocks, such as limestone and shale, are relatively rare, save in a region where the former rocks are absent and the latter practically the only ones present.

River gravels of the Glacial period are of frequent occurrence throughout New England and the northern part of North America. They lie usually along the margins and at the heads of flat valleys of varying size, marking the courses and outlets of the many streams that issued from the front of the melting glacier.

The specimen in the collection gives but a very imperfect idea of the appearance of the gravel in its original position.

This can only be appreciated by seeing and studying numerous exposures in gravel-pits or road cuts, where the interbedding of gravel and sand layers and the variations in coarseness and fineness are shown. River deposits vary in coarseness according to the velocity of the water by which they were deposited, from the finest mineral grains up to bowlders occasionally two feet and even more in diameter. A cabinet specimen must be taken from rather fine gravel.

As this gravel was deposited by waters issuing from the ice which occupied the Central Lowland of Connecticut, the predominating pebbles are from the trap sheets and the harder sandstone beds; but, as the ice carried bowlders of other rocks from the Western Highlands into the Central Lowland, pebbles of these rocks also may be found. Examination of the specimen shows pebbles of quartzite, glassy quartz from veins, granite, gneiss, and schists of different kinds. The schist fragments are scarce, and their average size is smaller than that of sandstone and trap pebbles. In general, the pebbles vary from an inch or two in diameter down to the dimensions of the mineral grains of which the rocks were composed. These grains, mostly of quartz and feldspar, occasionally of garnet, hornblende, mica, and magnetite, form the sand matrix for the pebbles. The ferric oxide, which gives to the sandstone its red or brown color, also stains the fragments of quartz and feldspar which form the gravel.

Gravel deposited by water is characterized by the rounded shape of its pebbles; but the degree of rounding varies with the amount of rolling that the pebbles have suffered. The sandstone pebbles in the specimen, although possessing rough surfaces, are the most rounded, because the component grains were loosened from their cement more easily than the crystals in trap, granite, and other crystalline rocks were detached from each other. The least rounded pebbles are quartzite, the hardest of all rocks. That the sandstone pebbles are far from being completely rounded may be seen by comparing them with the beach pebble (No. 9); on the other hand, they are decidedly more rounded than the glaciated pebble (No. 4), which has not been rolled at all by water. This partially rounded character shows that the pebbles could not have been transported a great

distance by water, and their average size, one inch or less, is evidence that the velocity of the flowing water could not have been very great.

No. 6. Sand, Glacial Period.

Westville, New Haven, Conn.

Little remains to be said of this specimen. Its origin and composition is essentially the same as that of the gravel (No. 5), save that it was deposited by more slowly flowing water, and rock pebbles are very small and scarce. The mineral grains composing the sand are mostly quartz, with considerable feldspar, the former usually colorless and glassy, the latter white to pink, opaque, and often showing smooth cleavage surfaces. The other minerals, present in small amounts, are garnet, hornblende, mica, epidote and magnetite, the last in minute granules detected only by passing a magnet through the sand. If this test is made it will be found that light-colored grains sometimes adhere to the magnet. These are minute rock fragments which contain enough magnetite to be influenced by the magnet. Other minerals, such as zircon, are probably present in small amounts, but it is impossible to distinguish such fine grains from quartz without the aid of a microscope. The angular character of the grains is very pronounced. This specimen of sand was taken from the same pit as the gravel specimen, and shows how change in the velocity of water may vary the character of the material deposited.

No. 7. Clay, Glacial Period.

Quinnipiac Valley, Hamden, Conn.

Glacial clay is made up of the extremely fine material carried by streams from the melting glacier and deposited in lakes and estuaries along its front. It is never a pure clay, but is composed largely of very fine rock powder, or "rock flour," resulting from the grinding action of the ice upon rock surfaces. In other words, it is the finest material that is found in till. The composition and color of glacial clays vary in different parts of the country, according to the rocks from which they are derived. Those in limestone regions have a high percentage of calcium and magnesium carbonates. Most of those in New England

have small or moderate amounts of iron, lime, magnesia, and alkalies, and are blue in color, owing to the ferrous condition of the iron; those found in the lowland of southern Connecticut — at Berlin, Middletown, and North Haven — are brown, owing to the ferric state of the iron.

The glacial clays of Connecticut are principally located along the Connecticut river valley from the Massachusetts boundary to Hartford; at Berlin and along the Sebethe river valley from Berlin to Middletown and Cromwell; and along the borders of the lower Quinnipiac from North Haven station southward to New Haven. The continuity and extent of workable clay is best seen by referring to the map and sections in Bulletin 4 of the State Survey. Other small deposits occur in the state, but are of no importance at present.

The clay consisted originally of alternate layers of fine, plastic or "strong" clay, and "quicksand" or sandy clay. The latter, though very fine, lacks the high degree of plasticity possessed by the strong clay. The color of the clay in place is chocolate brown, but becomes lighter on drying. In the dry specimen, the layers of strong clay retain their form, but the sandy layers crumble, causing the whole to disintegrate. The relative thickness of the different layers varies: in some cases they are uniform and from one-half an inch to an inch thick; but in other cases the sandy layers are thicker than the clay layers, and may even exceed a foot in thickness. The nearer the margin of the deposit, the more prominent are the sandy layers likely to be.*

The material composing the clay was derived from the red and brown sandstones and shales of the Triassic basin, and the fine red or brown cement which colored these rocks has also colored the clay.

The banded character may perhaps be explained as follows:†— During the warmer seasons, floods from the ice front carried the fine sand and clay into the lakes, but during the winters the ground was largely snow-covered, and the streams could bring in but little sediment. The sandy portion settled with comparative rapidity, while the finer clay settled so slowly that its

* This description, save as regards the color, holds also for the blue clays found around and north of Hartford.

† See also U. S. G. S., Folio 50, p. 7, by Prof. B. K. Emerson.

deposition continued all through the winter and even into the next melting season, when it became mingled with the next accession of sand. Yearly repetition of this process built up the banded deposits of "strong" clay and "quicksand."

The history of the clay deposits is summed up as follows:— When the ice sheet had begun to melt away, the continent was depressed to the north, diminishing or abolishing the southward slope of the river valleys and resulting in a sluggish drainage. Consequently, lakes formed at the ice front; and, while gravel and coarse sand were deposited at the ice margin in deltas, the finest material settled in the more quiet waters of the lakes. When, finally, the ice sheet had disappeared, the continent was re-elevated to the north, and the lakes were drained, leaving the flat clay deposits exposed and accessible for use.

Owing to the high percentage of iron, lime, magnesia, and alkalies, impurities which make the clay fusible, the glacial clays are limited in use to brick and earthenware manufacture. They are well suited for these uses, being very plastic and burning to a dense body at a relatively low temperature. The natural clay is usually too plastic to be used alone for brick-making, and is mixed either with sand or sandy clay to lessen its plasticity.

No. 8. Clay Concretions.

Elmwood, West Hartford, Conn.

Concretions are formed by the collecting of mineral matter deposited around some central point or nucleus. Various minerals may, under proper conditions, develop a concretionary form. The concretions characteristic of clay deposits are often called "claystones" or "clay dogs." The latter name is common in Connecticut, and was originally given to forms resulting from the coalescence of a number of the typical spheroidal concretions, which in some cases rudely resembled a dog in shape. A great variety of shapes may be found.

Clay concretions are composed principally of lime carbonate ($CaCO_3$), in which are enclosed fine grains of sand and clay. If a small fragment of a concretion is placed in dilute hydrochloric acid (one part acid to six water) the lime carbonate will gradually dissolve, leaving finally a greater or less residue consisting of grains of sand and clay.

In the Connecticut clay-pits it is to be observed that concretions abound in certain sections and are absent in others; further, that they occur in the thin laminæ of quicksand and not in those of "strong" clay. This distribution may be explained as follows: The clays, save close to the surface, usually contain a large amount of water, which flows along the porous sandy laminæ, but not along the layers of the compact "strong" clay. The surface water, when first entering the clay, begins to take into solution as carbonates or bicarbonates the lime and other soluble constituents of the clay, and quickly becomes saturated. The lime carbonate is then precipitated at some favorable point or points, and collects around grains of sand which serve as nuclei. If the sandy layers in the clay were thick enough, these growths or concretions would be expected to assume a spherical form; but, usually, the layers are so thin that the concretions can grow only laterally in the plane of the stratum and develop a circular, disc-like form.

If the several nuclei are sufficiently far apart these discs may be perfectly circular; but, if they are not, two or more discs will grow together, as shown in the specimens. This coalescence is in general the cause of the curious forms for which clay concretions are noted. The concentric lines which are usually present on the surfaces of concretions mark interruptions in growth, the water ceasing to deposit for a time and later recommencing.

The color of clay concretions varies with the color of the material in which they grow; thus the light-colored specimens were formed in fine, light-colored material, and the grains are, in consequence, almost invisible; the brown specimens were formed in a coarser layer of brown quicksand, and the grains, besides giving their color to the mass, are visible as distinct grains embedded in the matrix of lime carbonate. In general, the former light colored variety is found in pits of blue clay in and north of Hartford; the brown variety in the brown clays south of that city. The clay at Elmwood is intermediate in character, containing blue as well as brown layers, and both varieties of concretions are found there.

Clay concretions are of no use, and are troublesome to brick-makers. If they are not removed from the clay, they give off carbon dioxide (CO_2) when burned, and become quicklime.

Later, when the bricks are exposed to air and rain, this quicklime absorbs water and swells with sufficient force to burst or spoil the brick.

No. 9. Beach Pebble.

Niantic, East Lyme, Conn.

Beach pebbles are those that have been rolled to and fro by the waves until their sharp corners have been all well rounded. They may consist of any kind of rock, but more commonly of the hardest types, and may be derived from any formation along the coast. Thus, in New England, they come from fragments broken away from ledges, from the bowlders in till, or from pebbles of glacial river gravels.

A study of the distribution and character of pebbles on an ideal beach should begin at the base of a rock ledge (or of a till deposit), marking the upper limit of the beach, where large angular bowlders will be found to predominate. In passing towards the low-water mark, a gradual diminution in size will be observed, together with a disappearance of angular edges, until well rounded pebbles, about the size of a hen's egg, predominate. From this point onward the pebbles will grow smaller and fewer until they finally grade into sand.

These changes are due to the different intensities of wave action. The upper limit of the beach is only subjected to wave action during storms and flood tides. Here the repeated beating of large waves will in time dislodge blocks of stone from the ledge, and strew them along its base. These blocks are now further broken by the impact of the water and of smaller fragments carried by it, and gradually diminish in size. The pieces broken from them are rolled outward by the undertow and are ground together, the smallest fragments traveling farthest. This process of breaking and grinding continues until the smallest fragments, which suffer the most grinding and rolling, attain a fairly well rounded form. The fine material ground from them is carried farther away from the shore and deposited in the deeper and less turbulent water. The strongest wave action, and consequently the maximum grinding of rock material, is where the waves break against the shore. It gradually diminishes as the water deepens.

The specimen is moderately round, but, owing to the solution

of some of the mineral grains, the surface is not smooth. It is neither angular nor subangular, but the shape may be far from spherical. The specimens collected are chiefly of granite and gneiss, which are the most common rocks along the Connecticut shore. This water-worn pebble should be compared with the subangular glaciated pebble (Specimen No. 4).

No. 10. Magnetite and Garnet Sand.

Savin Rock, Orange, Conn.

The above name refers to sand whose principal constituents are the heavy minerals, magnetite and garnet. Another less specific name for sands of this character is "black sands." They have the same general characters as any water-deposited sand, and may be formed either in river beds or on beaches. They differ only in containing a predominance of heavy minerals. This difference means that they must have been deposited where the motion of the river or waves was too rapid to allow a deposition of fine grains of the lighter, more common minerals, quartz, feldspar, and mica. These minerals are readily seen to be present, but in grains larger than the magnetite or garnet, their finer grains having been carried farther and deposited in more quiet waters.

The specimen in the collection was taken from a place where the sea waves had acted upon ledges of chlorite chist (Specimen No. 30), a soft rock containing a considerable amount of magnetite in minute grains. The garnet is found in larger or smaller amounts in most rocks which have suffered severely from regional metamorphism. It is not, however, evident in this chlorite schist nor in the till which caps it, and thus offers an interesting example of the collection and concentration of a minute amount of heavy minerals into noticeable deposits through wave action. The transporting power of the inrushing waves is stronger than that of the undertow, and thus, as the grains of these heavy minerals are set free, they tend to be swept up on the beach rather than back into deeper water, and are concentrated at the highest line of wave action, while the micaceous chlorite and other light grains are carried outward into more quiet water.

The specimen needs no special description. The magnetite and garnet are both easily recognized by their color, the former

also by its magnetic properties. The other minerals present are practically the same as in Specimen No. 6.

Black sands may be valuable for certain minerals that they contain. Magnetite sand has been used as an ore of iron, but usually, as in the present instance, occurs in too small quantity to permit profitable working. The garnet grains also might be valuable for abrasive purposes, were it not for the difficulty of concentrating them and the small extent of the deposit.

ORGANIC DEPOSITS.

In regions of stagnant drainage, where the ground is at least moist throughout the year, deposits of organic origin accumulate which cannot be classed with either the residual or the transported materials described in the previous sections, since they were never a part of the subjacent rock formations nor of rock formations elsewhere.

No. 11. Peat.

Quinnipiac Valley, Hamden, Conn.

Peat consists essentially of partially decomposed vegetable matter, and represents the first stage in the transformation of vegetable matter into coal. Peat is derived from certain kinds of mosses which grow around the margins of ponds, and from swamp and marsh vegetation of various kinds. The necessary condition to form peat is that the vegetation be decomposed where it is excluded from direct contact with the air. Plant matter consists essentially of carbon, oxygen, and hydrogen. When decomposition takes place, oxygen from the air, in addition to the oxygen already present in the plant, unites with hydrogen to form water (H_2O) and with carbon to form carbon dioxide (CO_2). This process continues until the dead plant has disappeared. If, however, the plant is partially buried under swamp accumulation and cannot be attacked directly by the oxygen in air, it decomposes without complete oxidation. Some of the hydrogen and oxygen of the vegetable matter unite, forming water (H_2O); some of the hydrogen and carbon form marsh gas (CH_4); some of the oxygen and carbon form carbon dioxide (CO_2); and, when all the oxygen and hydrogen have been thus eliminated, a residue of carbon remains. This process goes on

very slowly. A variety of hydrocarbons very rich in carbon are formed in the course of the process. Carbon chemically free does not exist in peat nor even in ordinary coal.

Peat occurs in the salt marshes along the Connecticut shore, and may also be found in fresh-water swamps or bogs.

The specimen, taken from a salt marsh, consists of blades of marsh grass in all stages of decomposition, mixed with a certain amount of black (carbonaceous) mud. The peat at this place forms a layer three or four feet thick overlying brick clay (Specimen No. 7). It grades upward into the living marsh growth, and the character of the change from grass to peat is clearly seen. A factor favoring the accumulation of peat in this and other salt marshes along the Sound is the fact that the coast is at present slowly sinking at about the rate of one-eighth of an inch a year. Thus, although a new supply of vegetation is added every summer, the marsh surface is not brought above the level of high tides, and decomposition of the successive accumulations takes place without contact with the air. The disadvantage of the covering of the marsh by tides is, however, that each inundation brings a small amount of mud, rendering portions of the peat impure.

Peat in foreign countries is used to a considerable extent as a fuel, but has seldom been utilized in this country, owing chiefly to the abundance of coal. Recent tests by the United States Geological Survey have shown, however, that peat is a very valuable fuel for the generation of gas. It is used considerably throughout New England as a fertilizer, and is spoken of as "black muck."

Chapter II.

THE OLDER SEDIMENTARY FORMATIONS.

MECHANICAL DEPOSITS.

The term "older sedimentary formations," as here used, applies to deposits which have become transformed into solid rock. The order followed in this chapter is the same as that in the previous one, beginning with the material of coarsest texture and passing to those progressively finer and of more complex origin.

Connecticut is very poor in unmetamorphosed sedimentary rocks, the occurrences being restricted to the Triassic formation which forms the floor of the Central Lowland. Sedimentary rocks older than the Triassic once existed in considerable variety, but within the limits of the state they were universally mashed and recrystallized previous to the Triassic, and are now classed as metamorphic. The consolidated but unmetamorphosed sedimentary rocks of the state all belong to the class of mechanical sediments. The great group of chemical sedimentary rocks is entirely unrepresented save by a few impure calcareous bands in the Triassic shales.

No. 12. Conglomerate.

Portland, Conn.

Conglomerate, sandstone, and shale are sedimentary rocks, composed, respectively, of consolidated gravel, sand, and clay; and the variations which occur in the unconsolidated sediments reappear in the consolidated types. Thus conglomerate may be coarse or fine; its pebbles may represent various rocks, and may be more or less rounded. The name conglomerate is derived from the Latin and means "heaped together."

The Triassic conglomerates, represented by Specimen No. 12, lie mostly near the eastern and the western margin of the Triassic basin of central Connecticut, and the pebbles vary from over a

foot in diameter to a small fraction of an inch, the finer-grained conglomerates grading into sandstone. At Portland, where the extensive quarries show the stone in place, conglomerate, sandstone and shale are interbedded.

The conglomerate owes its brown color to the ferric oxide in the cementing material. This consists of fine sand and clay rich in the iron oxide. The pebbles in the specimens collected are not large. They seldom show well rounded surfaces; and that fact indicates that the distances to which the pebbles were carried from their source must have been short. They consist mostly of quartz, and coarse crystalline fragments of pink to red feldspar, the latter readily recognized by their perfect cleavage surfaces. The less prominent pebbles consist of granite, gneiss, mica schist, and chlorite schist, the two latter kinds occurring in the form of flat fragments. These different kinds of pebbles are probably not all present in any single specimen. The pebbles are cemented only where they touch one another, and the rock has therefore a very porous character. The subangular or even angular character of the pebbles, and the noteworthy presence of pebbles of the soft chlorite schist, show that the materials have been transported only a short distance.

The rocks from which the pebbles in the conglomerate were derived are found in the crystalline formations in the adjacent Eastern Highland of Connecticut. During the Triassic age, conditions were such that these rocks disintegrated into fragments without suffering much chemical decomposition. These fragments, together with the residual ferruginous clay, were carried rapidly away by torrents, and deposited in the valley between the Eastern and the Western Highland. Opinions differ as to whether the valley was an estuary, a lake, or merely a broad plain receiving deposits of river waste. Accumulation continued in this manner on the slowly subsiding floor of the valley, until the sedimentary rock attained a great thickness, and the lower beds were consolidated by the weight of the overlying beds in the presence of that heat which is found at moderate depths. Subsequent erosion has brought these consolidated beds again to the surface.

The Triassic conglomerate is useful as a building stone; but, owing to its being of less attractive appearance than the sandstone, its use is largely confined to bridges and foundations.

No. 13. Arkose.

Fair Haven, New Haven, Conn.

Arkose is the name given to a sandstone made up largely of feldspar, in distinction from the usual variety which consists essentially of quartz grains. Arkose is formed under the conditions mentioned on page 155 in the description of conglomerate, and differs from conglomerate only in the absence of the larger, rounded pebbles. Grains of the various rock-forming minerals may all be present.

All the Triassic sandstone of Connecticut is to some extent an arkose, and it is much more abundant than the conglomerate.

The mineral grains visible to the naked eye are feldspar and quartz, with a subordinate amount of mica, in a ferruginous cement similar to that of the conglomerate. In fact, the principal difference between these two rock types is the size of the component fragments. A microscopic study of a similar specimen, from Portland, Conn., showed the following minerals to be present: — quartz, feldspar (including orthoclase, microcline, and plagioclase), white and black mica, garnet, chlorite, epidote, magnetite, and minute pebbles of quartzite and chlorite schist. The cementing material, besides ferruginous clay, included a little calcium carbonate ($CaCO_3$). Some of these constituents may or may not be present in the specimens collected. This list emphasizes still more the fact that arkose is a sedimentary rock composed of undecomposed grains of disintegrated igneous rocks Those that contribute to the formation of arkose are chiefly granite, gneiss, and schist.

The history of the Triassic arkose is identical with that of the conglomerate, save that it was deposited by slower currents of water. The arkose, or "brownstone," as it is known commercially, is famous as a building stone, and is to be seen in many "brownstone fronts" of buildings in various cities. That from New Haven is unusually coarse in grain, often approaching the texture of a fine-grained conglomerate. Where the feldspar is especially abundant and coarse, the rock is sometimes mistaken for a red granite; and is, in fact, while truly a sedimentary rock, also a recomposed granite.

No. 14. Red Shale.

Portland, Conn.

The red, or brown, Triassic shale lies mostly in the central part of the Triassic basin, and is also found interbedded with arkose and conglomerate in the eastern part, as at Portland, Conn., where the specimens were collected. The shale differs from the arkose principally in fineness of grain. It contains the same mineral constituents but in different proportions. The principal constituents are ferruginous clay (the cement of the conglomerate and arkose) and light flakes of mica. The mica flakes lie along the bedding planes. A microscope would probably reveal the presence of minute quartz granules, known as "quartz flour," but the hardened red clay and mica are the only minerals visible to the naked eye. The character of the rock indicates that the material was deposited by sluggish currents of water.

A striking feature of the shale in the ledge is the almost constant presence of rudely hexagonal mud-cracks, precisely like those so often seen in the dried mud of river or tidal flats. This network of fossil mud-cracks, unfortunately, is on too large a scale to be represented in a hand specimen, though some specimens may show a part of the course of a crack. These markings indicate that, soon after the mud was deposited, and before a new layer was deposited over it, the water withdrew from the locality, leaving the mud exposed to the wind and sun, which caused it to dry, shrink, and crack. The cracks were then filled by sand, drifted either by the wind or by the returning waters. The whole was then preserved by the deposition of overlying layers.

A striking feature in several of the specimens collected is the presence of small spots and irregular lines or trails. The latter in some cases lie wholly along the bedding planes, and in others pass obliquely or perpendicularly through them, their ends appearing as spots on the bedding planes. Though the origin of these markings is not certain, they are very suggestive of worm-trails and borings.

Large specimens of the shale, on exhibition in several museums in Connecticut and elsewhere, show in addition to mud-cracks and these possible worm-trails, excellent examples of

fossil rain-prints, ripple-marks, rill-marks, and footprints of huge reptiles which lived during Triassic time.

The history of the Triassic shale is the same as that of the conglomerate and arkose, save that it was deposited in quiet or sluggish water. Shale in some parts of the country is ground and made into brick or into certain colored paints; but the abundance of the more easily worked clay of the Glacial period in Connecticut bars this shale from use.

No. 15. Black Shale.

Lake Saltonstall, Branford, Conn.

Black shale also occurs in the Triassic basin, but is very limited in extent. Outcrops of it have been noted near the south end of Lake Saltonstall in Branford, at Gillett's mills in Durham, in the stream bed about half a mile northwest of Westfield village in Middletown, north of Rocky Hill village, and in North Bloomfield.

It consists, like the red shale (Specimen No. 14), principally of clay and mica, the latter in fine, shiny flakes lying along the planes of bedding. The black color is due to carbonaceous matter, derived from decaying plants.

Black shale, deposited between beds of red shale, indicates that occasionally swampy conditions prevailed in a region that often was bared by the retreating waters and dried. Fossil fishes have been found in the black shale, but never in the red shale.

Black shale has no commercial value. Certain strata of it, especially rich in carbon, have led to the search for coal beds; but none have ever been discovered, nor is there any ground for expectation that in Connecticut any coal beds will ever be found.

Chapter III.

THE IGNEOUS FORMATIONS.

The igneous rocks, formed by the consolidation of molten magma at or beneath the surface, are described in the following order: — first, the acidic rocks, or those rich in silica; second, the basic rocks, or those poor in silica. Only an incomplete idea of the whole series of igneous rocks can be gained in this chapter, as the only acidic rocks which have not suffered sufficient alteration to be classed as metamorphic rocks are typical granites, and the only basic rocks not metamorphosed are gabbro, diabase, and basalt — the three being different forms of chemically identical rocks. Other types chemically intermediate between granite and gabbro, on account of their altered character are included among the metamorphic rocks in the following chapter.

THE GRANITES.

The granites are rocks consisting essentially of quartz and alkali feldspar, which have solidified at a great depth beneath the surface and often in great mass, with the result that they are coarsely crystalline and the individual minerals therefore clearly distinguishable. The varieties are due partly to the character of the crystallization, and partly to the kinds of minerals present in addition to the essential quartz and feldspar.

No. 16. Thomaston Granite.

Thomaston, Conn.

The Thomaston granite is, so far as known, the youngest formation in the Western Highland of Connecticut, except local intrusions, such as pegmatite and diabase dikes. It occupies limited areas, as shown on the Geological Map of Connecticut,* throughout this region, and is well developed at Thomaston.

The typical rock is a light colored biotite granite of medium to fine grain. The specimens collected show practically no

* Bulletin No. 7, Conn. State Geol. and Nat. Hist. Surv.

gneissic structure (*i. e.,* parallel arrangement of the mineral grains), but in many outcrops of the granite this structure is very marked.

The minerals visible to the naked eye are feldspar, quartz, biotite, and muscovite. The feldspar occurs in small crystalline grains, distinguished by their white, opaque appearance, and the perfect, glistening cleavage surfaces. It is the most abundant mineral in the rock. The quartz occurs in smaller, glassy, irregular grains. It is easily distinguished from the feldspar. The biotite is disseminated in small black flakes, but its quantity varies somewhat in different parts of the rock. This variation gives two kinds of stone: that with more biotite, light gray in color and easily worked; that with less biotite, nearly white in color, harder, and less easily worked. The muscovite is less noticeable than the biotite owing to its being almost colorless.

At several times before the close of the Paleozoic, the whole of western Connecticut was subjected to enormous horizontal compression, which was sufficient to fold and transform the rocks into their present complicated relations. Molten granite was at times forced upward through fissures in which it solidified, forming dikes or sheets and masses of considerable extent. Where the compression was more marked, and continued after the intruded granite had begun to harden, its influence on the granite developed the gneissic structure; where the compression was less marked, the massive structure of the granite is preserved.

Long continued erosion, following the period of compression, has gradually worn away the overlying rocks, until, as seen to-day, the dikes and masses of the Thomaston granite have been exposed. If uplift and erosion shall continue until thousands of feet more of the rocks now at the surface are worn away, it is thought that the many isolated areas of granite shown on the map will gradually merge into larger areas, since masses superficially separate are doubtless united below.

The Thomaston granite, owing to its white color, is a very attractive building stone. It is the lightest colored granite quarried in Connecticut. The quarried blocks are easily dressed, but the quarrying is often rendered difficult and expensive,

owing to the small size of the granite dikes or masses, and the consequent necessity of removing a large amount of the adjacent rock as waste.

No. 17. Westerly Granite.

Niantic, East Lyme, Conn.

The Westerly granite, like the Thomaston, occurs as intrusive dikes in other granites and gneisses. The dikes of Westerly granite occur along the shore of Long Island Sound, especially from the vicinity of Westerly, Rhode Island, westward as far as East Lyme, in Connecticut. The size of these dikes is not definitely known, but the fact that some of them afford profitable quarries shows that their width and length is considerable.

Not all the dikes are now worked, but quarrying is carried on at Westerly, Rhode Island, and at Niantic, Millstone Point, and Waterford, Connecticut. Small abandoned quarry pits are frequent at other points in Connecticut between New London and the Rhode Island boundary. The most abundant and largest quarries are at Westerly, and the stone is therefore called the Westerly granite.

The rock is an even, fine-grained granite, shading from pink to gray in color. The visible minerals are feldspar, quartz, and mica, while other minerals, as magnetite, zircon, and apatite, occur in microscopic crystals. All the pink grains which give the color to the rock are feldspar. Its crystallographic character, owing to the fineness of grain, is not easily seen, but close examination will show the smooth, glistening cleavage surfaces. The quartz occurs in rather dark, small, glassy grains among the feldspar. The mica, occurring in tiny flakes sprinkled evenly throughout the rock, is mostly the black variety (biotite), but a few flakes of the white mica (muscovite) may sometimes be seen by the unaided eye.

This description is that of a typical granite, except for the rather unusually fine grain. This is doubtless due to the occurrence of the granite in dikes. When large masses of granite cool slowly, far below the surface, they can develop fairly large crystals; but, when branches are sent upward from these masses into fissures to form dikes, they cool much more rapidly, and the growing crystals have not time to attain the maximum size.

As the Westerly granite forms dikes in all the other rocks in the vicinity, it is undoubtedly younger than the former, and may be considered the youngest pre-Triassic rock in eastern Connecticut. Its history is practically the same as that of the Thomaston granite, the latest pre-Triassic intrusive rock of western Connecticut.

The Westerly granite is a well-known stone for monumental work, and is frequently seen in cemeteries and in public memorials. Both gray and pink stone are quarried, the gray more frequently, but the pink variety predominates in Connecticut.

No. 18. Stony Creek Granite.

Stony Creek, Branford, Conn.

The Stony Creek granite appears in a semicircular area about five miles in diameter in Branford and in Guilford, the outcrop passing on the south beneath Long Island Sound. This area includes both granite, illustrated by Specimen No. 18, and granite-gneiss, represented by Specimen No. 24. Another smaller area of the same rocks appears on the shore a little farther east.

This granite is a very uneven, coarse-grained, red rock, very different from the even, fine-grained Westerly stone; but both are good examples of granite. The Stony Creek, however, gives a better opportunity for the study of the constituent minerals. Those visible to the naked eye are red and white feldspar, quartz, a little biotite, magnetite, and pyrite. The red feldspar is the potash variety (orthoclase or microcline). It forms the largest crystals in the rock, and shows perfect cleavage faces. Some crystals, if studied closely, are seen to show the two cleavage directions at right angles to each other. These two cleavages are present in all feldspars, but in granites the crystals are usually too small to exhibit them both clearly. Some crystals may show the characteristic luster of the cleavage surface over half their area only; but, if the specimen is rotated through a small angle, the lustrous reflection will disappear from the surface where it was seen before, and will appear on the other half of the crystal. This phenomenon is due to *twinning*. The feldspar is a double crystal, made up of two crystals, with molecular structure reversed in direction, each with its own cleavage. This particular kind of a twin crystal is called a

"Carlsbad twin," from Carlsbad, Bohemia, where it is excellently illustrated. Carlsbad twinning is a common occurrence in all feldspars, but is only detected in fairly large crystals without the aid of the compound microscope.

The white feldspar is the soda variety (albite or acid oligoclase). It is less abundant than the orthoclase, and forms much smaller crystals. Its cleavage, though not so evident, is similar to that of the orthoclase. It may also exhibit the Carlsbad twinning. If the white cleavage surfaces are studied with a lens, some of them will show a series of very fine parallel lines, or striations, extending across the crystal. These lines are also due to twinning. What is apparently one crystal, is really a multiple crystal composed of a large number of very small flat crystals side by side. Every one of the lines, or striations, represents one of these flat crystals. This multiple twinning is called *albite twinning,* and is common to all the soda and lime varieties of feldspar (plagioclase).* This most important character of the albite is detected with difficulty.

The quartz is typical, forming irregular, transparent, but rather dark and smoky-colored grains. Though a principal constituent of the rock, it is decidedly less abundant than the feldspar, as is true of all typical granites.

The biotite (black mica) occurs in shiny flakes and crystals which may attain considerable size. The crystals consist practically of a series of the flakes in a pile; in other words, each flake is a cleavage fragment of mica. The crystals usually show no definite outline, and often seem to spread out into short streaky areas. Sometimes they appear ragged, as if they had been partly eaten away and encroached upon by the feldspar and quartz. This is not an uncommon feature of biotite, but, like many of the characters mentioned in this description, is not often seen without the aid of a microscope.

The magnetite is scattered throughout the rock in rather small grains of metallic luster, black and shiny on the rough surface of the specimen, and gray on the polished surface. It

*Soda feldspar is nearly always present in granites, but is easily detected only in coarse varieties. Both the Thomaston and Westerly granites contain it; but in the former it can only rarely be distinguished from the potash feldspar, which is also white, while in the latter the grain is so fine that the small white crystals are not readily noticed. Close inspection will, however, show them to be present.

is best seen by holding the polished surface so as to reflect light to the eye.

The pyrite, though probably present in every specimen, is not abundant, and but few grains are present in a single specimen. It is readily recognized by its brass-yellow color and metallic luster.

The relations of the different minerals to one another may be studied most advantageously in a thin section of the rock with the aid of a microscope; but close study of the specimen with a lens will reveal all, or most, of them. It will be seen that the magnetite and pyrite are usually enclosed by one or another of the other minerals; therefore they must have been the first minerals to crystallize from the molten mass, and the other minerals, forming later, crystallized around them. The biotite is usually enclosed in feldspar or quartz; and often includes, or is attached to, a grain of magnetite. Biotite must, accordingly, have formed before the feldspar and quartz, but after the magnetite; and often the solid grains of magnetite served as nuclei around which the biotite crystallized. The largest biotite crystals are most frequently associated with magnetite grains. The white soda feldspar is usually partially or completely enclosed in the red potash feldspar or in quartz; but the two latter minerals are very rarely, if ever, found enclosed in the white feldspar. The white feldspar, then, must, as a whole, have crystallized before the red feldspar and quartz. The red feldspar crystals often show fairly definite boundaries, as though they had room to develop approximately a crystal outline; but the quartz grains are mostly very irregular, and appear to fill the chinks between the feldspar crystals. These facts suggest that the quartz in general must have followed the potash feldspar in crystallizing; but small grains of quartz are also seen enclosed in feldspar, and must have crystallized before it. In general, these two minerals crystallized almost simultaneously; but the greater part of the feldspar crystallized before the quartz, forcing the latter to fill the irregular interspaces.

This order of crystallization is the normal order for granites and other acidic rocks. The metallic minerals crystallize first, followed successively by the black (ferromagnesian) minerals (pyroxene, biotite, and hornblende), the feldspars, and finally by quartz, if any is present

The Stony Creek granite is intrusive into the surrounding gneiss and schist, and is one of the younger rocks in the eastern crystalline area of Connecticut. The Stony Creek granite is an excellent stone for building and decoration, and is much used in the larger cities.

THE BASIC ROCKS.

No. 19. Preston Gabbro-diorite.

Preston, Conn.

Gabbro, a word of Italian origin, is the name given to granular igneous rocks, similar to granite in texture, but composed essentially of basic plagioclase feldspar and pyroxene. Its color, owing to the large amount of pyroxene, is darker than that of granite. It is a basic rock; that is, it contains a relatively small amount of silica, and a large amount of iron, lime, and magnesia, thus developing the lime-soda feldspar (basic plagioclase), and the ferromagnesian mineral, pyroxene.

Diorite is also a granular igneous rock, resembling a granite in texture, but consisting of plagioclase and either hornblende or biotite. Typical diorite contains hornblende. If biotite is present, the rock is called mica diorite.

Typical diorite is less basic than gabbro, and lies about midway between granite and gabbro in chemical composition; but some rocks consisting of plagioclase and hornblende are quite as basic as gabbro. In fact, a gabbro, if subjected to sufficient pressure in the presence of heat, may be transformed into a diorite, owing to the tendency of pyroxene, under pressure, to change to hornblende. When it can be proved that a rock, originally a gabbro, has been thus changed to a diorite, the rock in question is called a gabbro-diorite.

The Preston gabbro-diorite occupies a roughly oval area in the southeastern part of the state, mostly in the towns of Preston and Griswold, but extending southward into North Stonington and Ledyard. Its dimensions are approximately eight miles from north to south and three miles from east to west. It is most typically developed in the town of Preston, and thence derives its name.

The Preston gabbro-diorite is a coarse to medium-grained

rock, dark green in color. Its visible components are plagioclase, pyroxene, hornblende, and magnetite. It is somewhat difficult at first glance to distinguish the different minerals, as both the feldspar and the fibrous hornblende are dark colored; but the former may be recognized by its dark purplish, and the latter by its dark green, color. A lens is indispensable for the study of this rock. Close examination shows the purple plagioclase feldspar (labradorite) to be present usually in rectangular or lath-shaped crystals. The albite twinning (see page 163) is strongly developed in many crystals, and can sometimes be seen even without the aid of a lens. The purple color has been shown by examination with the compound microscope to be due to minute dust-like inclusions, probably of iron oxide. When the feldspar undergoes weathering, the color is lost and is replaced by white, due to the presence of kaolin. The white color is present in all specimens which show a weathered surface.

As shown by the microscope, both pyroxene and hornblende are present in the specimen. If the specimen be rotated, light will now and then be reflected from a considerable surface, or from several parallel surfaces in one area. These are the cleavage surfaces of large pyroxene crystals, varying from less than an inch to two inches or more in length. Each one includes a number of small lath-shaped plagioclase crystals. The feldspar, therefore, must have crystallized before the pyroxene — just the reverse of the normal order stated on page 164. The feldspar crystals are not arranged in any definite order in the pyroxene, but give it a mottled appearance. This arrangement of feldspar in pyroxene, from the fancied resemblance to the skin of a serpent, is known as the *ophitic* texture, from the Greek word for serpent.

The study of the rock in thin sections with the microscope has shown that the large pyroxene crystals do not terminate abruptly, but grade into areas of the finely fibrous green hornblende (uralite). Wherever pyroxene crystals are absent, the fibrous hornblende forms a felt-like mass which encloses the feldspar; and even within some pyroxene crystals the fine green fibres of the hornblende can be seen. It is evident from these facts that the pyroxene has partially changed to hornblende; and it seems probable that all the hornblende is secondary, having

been formed from the large pyroxene crystals, which originally made up the body of the rock and contained the feldspar and other minerals as inclusions.

Magnetite (or ilmenite) and pyrite, as usual, form rather small grains, but these are larger and far more abundant than in granite. The percentage of magnetite is greater than it seems, as many minute grains of it are concealed by the pyroxene and hornblende.

The gabbro was forced up from below into the surrounding sedimentary rocks in the form of an immense oval mass. Subsequently the whole region was subjected to great heat and lateral pressure, which folded and recrystallized the surrounding sedimentary formations into gneiss and schist. The tough, massive gabbro, however, was not so easily altered, and suffered only a partial change of its pyroxene into the green hornblende. The specimen is, then, strictly speaking, only partially converted into a gabbro-diorite; but the name is applied because the formation as a whole has suffered considerable alteration, and contains, in places, hornblende and no pyroxene. No marked gneissic or schistose structure was developed, except close to the borders of the mass. The great amount of erosion which followed these changes has brought the gabbro to the surface.

Gabbro and diorite are sometimes worked for building stone, and then called "black granite"; but they are less desirable than granite, on account of their somber color, their greater weight per cubic foot, and greater toughness. Both rocks are sometimes quarried for road metal, but are not so good as diabase or basalt for that purpose.

No. 20. Triassic Diabase.

West Haven, New Haven, Conn.

Diabase is a basic rock composed of the same minerals as gabbro, but finer-grained. It shows characteristically the ophitic texture (see p. 166), in that the feldspar crystals are enclosed in the pyroxene; but, in the present instance, the rock is so fine-grained that the texture can be recognized only by the aid of a strong lens or a compound microscope. Diabase occurs in dikes, or in sheets which have been intruded between beds of sedimentary rock. It marks the passage, both in geologic

position and in texture, between deep-seated gabbro and surface lava flows of basalt.

Diabase in Connecticut is confined mostly to the Central Lowland, where it occurs as dikes and intrusive sheets now broken by faults and tilted. The sheets are the more prominent, their eroded outcrops existing as long ridges near the western border of the Lowland. The dikes occur mostly in the southern part of the Lowland between Wallingford and New Haven.*

The rock, as shown by the specimen, is nearly black in color, and though not extremely fine-grained, is too fine to exhibit clearly its minerals and their arrangement to the unaided eye. Feldspar and pyroxene, the two essential minerals, are the only ones visible. The feldspar occurs in very small lath-shaped crystals, and occasionally may show the twinning striæ (p. 163). The pyroxene crystals, whose outlines can seldom be detected without a compound microscope, form the body or ground-mass of the rock, and enclose, or partially enclose, the feldspar, producing the ophitic or diabase texture. This texture is best exhibited on weathered surfaces, the bleached aspect of the feldspars distinguishing them readily from the iron-stained pyroxene. Magnetite and apatite are scattered through the rock in microscopic grains. To the former is due in part the rather high specific gravity of the rock.

The most significant features of this rock are its fine grain and ophitic texture. The former signifies fairly rapid cooling and consolidation, which take place only near the relatively cool walls of the dike or sheet, or near the surface.

During the deposition of the Triassic sedimentary rocks, there were repeated volcanic eruptions of basic lava. Where this basic lava flowed over the surface and consolidated, basalt (Specimen No. 21) was formed; where it hardened within fissures which afforded passage toward the surface, it developed the peculiar ophitic texture, and became diabase. Diabase dikes occur in various regions and are of different ages. Those which have been observed in Connecticut are mostly of Triassic age.

The diabase is characterized by a well-developed columnar structure. This regularity of jointing enables it to be readily quarried in blocks with smooth sides. The rock itself is exceed-

* See Geologic Map, Bull. 7, Conn. Geol. and Nat. Hist. Surv.

ingly tough, and the dust cements to a considerable degree when wet and then dried, especially if it is slightly altered by previous weathering. These qualities render it an admirable rock for road metal, and the diabase and the closely related basalt are the chief materials used on the finely macadamized roads of the adjacent region. Diabase is also used to some extent as a building stone. The joint faces of the columns are usually rust-stained by the action of percolating water, so that walls and buildings constructed of diabase show combinations of buff and dark gray. These rather somber colors, and especially the difficulty of working the stone into blocks of desirable shape and size, are the reasons for its sparing use as building material.

No. 21. Triassic Basalt.

Meriden, Conn.

Basalt is consolidated lava of the same chemical and mineral composition as gabbro and diabase, but incompletely crystallized and extremely fine-grained. It was originally forced upward from below and poured out over the surface of the surrounding region, cooling so quickly that there was not sufficient time for crystals to grow to a greater than microscopic size. Sometimes the cooling of lava is so rapid that practically no crystals at all can form, and the rock becomes a glass. The recent eruptions of the Hawaiian Islands are basaltic flows which at the surface have cooled rapidly to a black and more or less spongy glass.

The basalts of Connecticut outcrop in a series of large and small ridges extending along the central or west central part of the Central Lowland entirely across the state and well into Massachusetts. Totoket, Beseck, Higby, Lamentation, Cedar, Rattlesnake, and Talcott mountains, with the Hanging Hills of Meriden, are the most prominent of these ridges.

The color of the basalt is black in some specimens and red in others. The latter color results from the peroxidation of a part of the iron of the pyroxene. In all other respects the description is the same for both. The texture or grain of the rock is very compact, and no constituent minerals can be distinguished by the naked eye. The crystals that have formed are microscopic or nearly microscopic in size. The rounded white

areas are secondary deposits usually of calcite, sometimes of quartz or other minerals, in spheroidal or irregular cavities.

The cavities were formed in the following manner:—While the lava was beneath the surface in a molten state, it contained a considerable amount of very highly heated water vapor and other gases, which, owing to the great subterranean pressure, could not expand, but were held in solution in the molten rock, in a manner analogous to the condition of the carbon dioxide held under pressure in carbonated fluids. Later, when the lava had reached the surface, the pressure became so far diminished that the imprisoned vapor separated from the magma, and expanded with such force that it developed the cavities or *vesicles* in the rock. These vesicles were most abundant near the surface of the lava flow, where the pressure was least. The lava became solid while the heat was still sufficient to keep the water in the form of vapor. When finally the solid rock became cold, the steam condensed to water and disappeared through the pores of the rock, leaving the empty vesicles.

The rock now was acted upon by water, perhaps in part the water originally in the rock, and in part rain water that had worked downward through cracks and cavities. The result of this action was the dissolving of certain constituents in the rock, especially lime and silica, and also magnesia, iron, and alumina. These dissolved substances were carried by the percolating water into the vesicles, and there deposited as calcite, quartz, chlorite, and other minerals, until the cavities were completely filled. These fillings are commonly called *amygdules,* and the rock containing them is called an amygdaloidal rock, or simply *amygdaloid.**

Owing to its extremely dense character and high specific gravity, basalt, like diabase, is an excellent rock for road metal. The presence of considerable calcite adds to its cementing power, and still more increases its value for this purpose.

*The name "amygdule" is derived from the Greek for almond, owing to the almond-like shape of many amygdules.

Chapter IV.

THE METAMORPHIC FORMATIONS.

THE GNEISSES.

Gneiss was a name originally applied to rocks having the mineral composition of granite; but has now become a general structural term, connoting only parallel arrangement of the mineral grains and a highly crystalline texture. If pressure had been so great as to crush the grains and rearrange them still further in thin parallel sheets, the gneiss would have become a schist. In cases of such extreme pressure the feldspar is usually broken down chemically as well as mechanically, and transformed into mica and quartz. Thus the presence of feldspar usually in large amounts is the chief mineralogical distinction between gneisses and schists.

The presence of feldspar implies that gneisses are usually derived from igneous rocks; but they may also result from the metamorphism of conglomerate and arkose (see Specimens No. 12 and 13). In the former case the crystals in the igneous rock are simply rearranged in parallel position; in the latter, the fragments, whether pebbles or mineral grains, and the cementing material, lose their identity, and are made over by recrystallization into a solid, non-porous rock, just as truly crystalline as an igneous rock. Thus two distinct types of rock may, by metamorphism, become so similar that it is impossible to determine, especially from the study of specimens alone, whether they were originally sedimentary or igneous. A gneiss known to be derived from a granite is often called a *granite-gneiss;* one derived from a sedimentary rock is often called a *sedimentary gneiss.*

GNEISSES OF IGNEOUS ORIGIN.

No. 22. Prospect Porphyritic Granite-gneiss.

Derby, Conn.

The word *porphyritic* is applied to rocks in which one or more minerals occur in relatively large and well-shaped crystals

imbedded in a relatively fine ground-mass. Thus, as in the present instance, a granite or gneiss enclosing large feldspar crystals is a porphyritic granite or gneiss; a schist enclosing distinct crystals of garnet or staurolite is a porphyritic schist.

The Prospect granite-gneiss forms a narrow belt extending in a north-northeast direction from Stratford, on Long Island Sound, through Huntington, Derby, Ansonia, Seymour, Bethany, Prospect, Cheshire, and Southington, where it tapers out. It derives its name from the town of Prospect, where it is typically developed.

This rock contains the same minerals — quartz, feldspar, and biotite — as a typical granite, and differs from a granite only in presenting a parallel arrangement of the mineral constituents (gneissic structure). The gneissic structure or foliation is brought out most strongly by the biotite, whose small black flakes or scales lie in parallel planes. These planes serve as natural parting planes, along which the rock splits easily. They are so persistent that, if the specimen is examined on these natural cleavage surfaces, it seems to consist almost wholly of biotite. The true proportion of the mineral constituents is found by examination of the cross fractures at right angles to the planes of foliation.

The large white porphyritic crystals are commonly called *phenocrysts*. In the present instance they average one inch in length. When the rock is viewed in the wall of the quarry these phenocrysts are seen to be very numerous; but the small hand specimens rarely include more than one of them. In some specimens the phenocrysts are rectangular and show the characteristic cleavage of feldspar. These phenocrysts usually illustrate excellently the Carlsbad twinning (see p. 162). In other specimens, the phenocrysts are more or less lens-shaped. These also were originally rectangular, but the pressure that caused the development of the gneissic structure deformed and mashed them into the lenticular form. The phenocrysts are sometimes spotted by fine, dark grains, mostly of biotite, but sometimes of tourmaline.

Crystals so large and well-formed as these phenocrysts, must have grown while the remainder of the rock was still in a fluid or at least a semi-fluid condition; that is, before, or perhaps during,

its ascent from a deep-seated source, into the overlying formations. After the formation of the phenocrysts, the history of the Prospect granite-gneiss was essentially similar to that of the granites previously described, until after its consolidation. It was then, as were all the metamorphic rocks of Connecticut, subjected to great horizontal compression which mashed or granulated the quartz and feldspar of the rock mass and even some of the phenocrysts, and completely recrystallized the biotite, causing it to develop along parallel planes between the quartz and feldspar grains. All these events took place while the rock was still deeply buried. Only long-continued erosion has finally brought it to the surface.

The Prospect granite-gneiss splits readily, and is easily worked into building blocks; but, owing to the frequency of joints or seams, cannot yield very large blocks. It has also been used as crushed stone; but, like all granites, is inferior for this use to diabase and basalt.

No. 23. Danbury Granodiorite-gneiss.

Stevenson, Monroe, Conn.

Granodiorite, a word made by a contraction from granite-diorite, is the name of a rock intermediate between a granite and a quartz diorite; that is, it consists essentially of quartz, plagioclase feldspar, alkaline feldspar, and biotite or hornblende. The compound polarizing microscope shows the plagioclase to be more prominent than orthoclase, but the latter and quartz are sufficiently abundant to give the rock the appearance of a true granite. The distinction between granite and granodiorite can usually be made only by microsopic examination.

The Danbury granodiorite-gneiss covers several areas of considerable size in southwestern Connecticut. The largest of these lies in parts of Danbury, Bethel, Newtown, and Monroe.

Its general aspect is similar to that of the Prospect granite-gneiss (Specimen No. 22) save that its gneissic structure is more strongly developed, and it is not so generally porphyritic. It frequently contains small intrusions or stringers of pegmatite between its foliation planes.

The geologic history is practically the same as that of the Prospect granite-gneiss; in fact, these two rocks are considered

simply variations of one great granitic mass. The chief value of this specimen is to show by comparison with No. 22 how similar two rocks may appear to the unaided eye, when there is really sufficient difference, from the chemical and mineralogical standpoints, to give them different names.

No. 24. Stony Creek Granite-gneiss.

Hoadley Point, Guilford, Conn.

This specimen represents a variation of the Stony Creek granite (Specimen No. 18). Its mineral composition is identical, and the gneissic structure is the one striking difference. The development of this structure is well illustrated. If the specimen is compared with No. 18, it will be noted that the red feldspars have been rearranged into elongated or lenticular bodies, which are not characterized by single large cleavage surfaces, but by a number of small ones. This fact indicates that the original feldspar has been broken or mashed into a granular mass of fragments. The mashing of feldspar, and also of quartz, is a characteristic feature of granite-gneiss, but is usually detected only by the aid of the microscope. The white feldspar and the quartz in the specimen are also granulated or mashed, but are less prominent.

The biotite, originally in distinct crystals or scales, has been distributed in parallel planes between the bands of feldspar and quartz, and appears in streaks on a surface of fracture transverse to the banding. These sheets of mica, when well developed, facilitate the splitting of the rock; but this character is better illustrated in Specimens Nos. 22, 23, and 25.

Minute crystals of garnet are commonly seen, especially with a lens, within the streaky areas of biotite.

The above facts throw light on the development of the gneissic structure. The rock yields to compression by shortening in the direction of pressure and lengthening in a direction at right angles to it. This readjustment is brought about by mashing of the feldspar and quartz grains into lens-shaped, granular bodies, lying with their long axes normal to the direction of pressure. The biotite, owing to its flaky character, is not granulated; but its cleavage plates are forced to slide over one another between the lens-shaped feldspar and quartz grains, and

what may have once been a distinct crystal becomes a streak of flakes. Biotite also may be completely recrystallized, so that its flakes will lie at right angles to the direction of pressure.

This variety of the so-called "Stony Creek granite" is also used for building purposes, and constitutes the pedestal of the Statue of Liberty in New York Harbor.

No. 25. Maromas Granite-gneiss.

Benvenue Quarry, Middletown, Conn.

The Maromas granite-gneiss occupies a roughly oval area, partly in Middletown and partly in Chatham, extending northward in a long narrow strip through Portland to South Glastonbury. Its name is taken from the village of Maromas on the southward bend of the Connecticut river, and almost in the center of the oval area.

The rock is a medium-grained, gray granite-gneiss. The gneissic structure is very well developed, and the rock splits very easily along the foliation planes. The chief minerals are feldspar, quartz, and biotite.

Unless carefully studied, the first two may be confused on account of their similar color and granular condition; but close inspection, especially with a lens, will show the bright, smooth cleavage surfaces of the feldspar. The lack of continuity of the cleavage surfaces, and the elongated, lenticular outline of the feldspar grains afford evidence of considerable compression or mashing. The quartz also is granulated, and has consequently lost much of its glassy luster; but glassy fragments of originally larger grains are frequent.

The biotite is spread in tiny flakes, or masses of flakes, along the foliation planes and around the feldspar and quartz lenses. Magnetite and pyrite are the only other minerals present. The former is masked by the biotite, and can only be detected by aid of a lens; the latter, when present, occurs in small grains, and is readily recognized by its brassy yellow color.

The Maromas granite-gneiss has practically the same geologic history as the Stony Creek (Specimen No. 24). Both when molten were forced from below into the overlying rocks, and were later, after becoming solid, subjected to pressure which mashed the feldspar and quartz into lens-shaped bodies, spread

out the biotite in distinct layers, and thereby developed the gneissic structure.

The rock has been used to a considerable extent as a building stone. The high degree of granulation renders it soft and readily worked. Several quarries have been opened, of which the Benvenue is the largest.

No. 26. Bristol Granite-gneiss.

Bristol, Conn.

The Bristol granite-gneiss occupies an area of pear-shaped outline, covering the central portion of Bristol. It extends westward just over the boundary into Plymouth, and northward nearly a mile into Burlington. The character of the rock varies in different places from a true granite to a diorite. The specimens collected represent the intermediate phase — granodiorite.

This rock is medium to coarse-grained, with the gneissic structure well developed wherever mica is plentiful. The chief minerals are quartz, plagioclase feldspar, biotite, chlorite, and garnet. The quartz is usually very finely granulated and cannot be distinguished from granulated feldspar. Its percentage varies in different specimens. In some it is very scarce, while in others it is more abundant. The feldspar is distinguished, as usual, by its glistening cleavage surfaces. If these surfaces are examined closely, preferably with a lens, the fine albite twinning striæ (see p. 40) will be very clearly seen in nearly all cases. This proves that the chief feldspar is plagioclase. The larger cleavage surfaces always lie within white granular areas. Orthoclase is present, but in small grains which can be detected only with a microscope.

The biotite is unevenly distributed. Where abundant, it is developed in imperfect wavy layers around or between the grains of feldspar. Where less abundant, its flakes generally lie in or nearly in the foliation planes, but the arrangement is not so clearly defined. Where the biotite is of a dark greenish color, it is due to the fact that it has been partially altered to chlorite — a dark green micaceous mineral. This alteration was effected by the action of heated water percolating through the rock when it was still at a considerable depth below the surface.

The garnet forms dark red, rounded crystal grains, and is

scattered throughout the whole rock; but it should be noted that the largest grains lie in the white areas where biotite is absent. This fact suggests that the biotite may originally have been more abundant, but has been decomposed in places where the iron, alumina, and silica have gathered to form the garnets. Biotite consists of silica, alumina, iron, magnesia, and potash; garnet (the most common variety), of silica, alumina, and iron, with usually a small amount of magnesia. Thus, to form garnet from biotite, potash and some magnesia must have been dissolved and removed, while the remaining constituents were dissolved, collected at certain points, and recrystallized. It should also be noted that the large garnet grains have not been granulated.

The only two important minerals in the rock previous to its alteration were plagioclase and biotite, with quartz prominent in some places but not in others. A rock composed of plagioclase and biotite is called a *mica diorite* (see definition of diorite, p. 88). If quartz and orthoclase are also present, as in this instance, the rock is a granodiorite.

The Bristol granodiorite-gneiss was originally a molten mass which worked upward into the overlying rock and crystallized. It was subjected to pressure which granulated the feldspar crystals and developed the gneissic structure. At the same time, or still later, highly heated water acted upon the biotite, dissolved the potash, and converted the remaining constituents partly into garnet and partly into chlorite. It is certain that the solid grains of garnet could not have existed before the granulation of the feldspar had been completed, for they too would have been granulated; and the chlorite was not developed until after the biotite had been spread out along the direction of foliation. The final period in this rock's history, as in that of nearly all the others, was its exposure at the present surface by the long continued erosion of the overlying rocks.

The forces which produced the changes in this rock left it full of small fractures which have since become partially cemented by filling with mineral matter deposited from percolating water. If the stone is quarried, it tends to break along these cemented cracks, or "blind seams," into irregular fragments, and the quarrying of large blocks is very difficult, if

not impossible. The irregular distribution of the biotite renders the strength of the stone less in certain places than in others. The stone must, therefore, be considered inferior as a building stone, although the combination of red garnet and white feldspar gives a pleasing color effect, especially on rough-faced blocks. The stone has been quarried to some extent for local use.

GNEISSES OF SEDIMENTARY ORIGIN.

No 27. Putnam Gneiss.

Putnam, Conn.

The Putnam gneiss is a very extensive and complex formation. It extends in a long, relatively narrow north-south belt almost across the eastern portion of the state, passing southward from Massachusetts through the towns of Thompson, Putnam, Brooklyn, Plainfield, Canterbury, Griswold, Lisbon, Preston, Norwich, and westward in a narrow belt through Bozrah into Salem. Isolated areas of it are found in other neighboring towns. It varies greatly in character, but is most typically developed in the vicinity of Putnam.

The many variations in the character of the rock render a complete description impossible. There are, accordingly, no strictly typical specimens. The formation, however, is as a whole characterized by rounded phenocrysts of feldspar scattered through a finer ground-mass of biotite with more or less quartz. It differs in this respect from any other rock in the state.

These feldspar crystals are abnormal in possessing so rounded an outline. They show brilliant, continuous cleavage surfaces, and a few may show albite twinning. Granulation is conspicuously absent. These facts lead to the conclusion that the feldspars must have been formed after the period of compression which developed the foliated or gneissic structure. Their rounded character may be due to the fact that in their growth they were obliged to crowd the surrounding minerals back.

The ground-mass of the rock varies. It may be an even-grained, gray gneiss, resembling a gray granite-gneiss in general appearance; or it may be so rich in biotite as to conceal completely all the other minerals except the phenocrysts above described. The latter variety is more properly called a schist.

Again either of these varieties may be penetrated by small vein-like stringers of granite along the foliation. If a specimen showed two or more of these granite injections along adjacent layers, they would give the impression that the rock was decidedly igneous in origin. Other less important variations might be added, but would serve only to confuse the reader. It must be repeated that the only typical character that can be illustrated in a single specimen is the presence of the rounded, ungranulated feldspar.

Garnet is sometimes present in rounded grains or crystals. Other minerals have been seen in the rock, but are either of rare occurrence or too minute to deserve mention here. The garnet, like the feldspar phenocrysts, must have formed subsequent to the development of the foliated structure.

The characters shown by a single specimen are not adequate to explain the geologic history of this rock; but study of the formation as a whole by geologists in Massachusetts and Connecticut has led to the following conclusions. The rock was originally of sedimentary origin, probably an impure sandstone, containing beds of arkose and shale, buried beneath the surface by continuous deposition. Later, the whole region was subjected to great horizontal pressure, which compressed and complexly folded the rocks, and to intrusions of granite which were forced up between the foliation planes of the rock. The effect of these various processes was to recrystallize completely the constituents of the rock. The impurities in the sandstone became biotite and garnet, and occasionally other minerals, resulting in a rock composed chiefly of quartz and biotite. This was invaded by the molten granite, which often formed large sheets, but also penetrated upward between the layers of schist, forming extremely thin sheets or "stringers." The round feldspar phenocrysts probably belong to these stringers; where the latter are so fine as to appear discontinuous, the feldspars stand out as isolated crystals. After this period of transformation from an impure sandstone or shale into the complex gneiss, the region was subjected to erosion until, at the present day, the Putnam gneiss has been exposed at the surface.

The Putnam gneiss practically has no economic value. It has been quarried to a slight extent, but its layers are generally too

contorted and irregular to afford good building material. Its generally dark color also renders it undesirable for this purpose.

GNEISSES OF UNKNOWN ORIGIN.

No. 28. Becket Gneiss.

West Cornwall, Conn.

The Becket gneiss occurs in several isolated areas throughout the western portion of Connecticut and Massachusetts and the esatern highlands of New York.* It is the oldest of all the rocks in the region, and, consequently, is exposed only where all later formations which once covered it have been eroded away.

The Becket gneiss is also a complex formation, and the name includes all rocks in the region, both igneous and sedimentary, which were formed before the Cambrian age. This ancient combination of rocks has been rendered still more complex by post-Cambrian intrusions of granite between the foliation planes.

Although there are several varieties of the Becket gneiss, it is always composed of quartz, feldspar, and biotite, and is very markedly foliated. The specimen in the collection may be considered typical. The extreme foliation has separated the biotite into distinct black layers, along which the rock splits very readily. Examination of the broad surfaces of the specimen shows these layers to consist of numberless minute flakes, firmly interlocked. Between these conspicuous layers of biotite are other extremely thin subordinate layers. Where weathering has taken place, the iron in the biotite has been oxidized to limonite.

The feldspar and quartz are so completely granulated that it is impossible to distinguish accurately between them, even with a lens. The original minerals are so completely flattened that they appear rather as thin plates than as lens-shaped bodies. Some of these are so long that they resemble small quartz veins, and it is possible that small quartz veins are actually present.

All that can be deduced from the character of the specimen is that the rock was originally either a biotite granite, or a sandstone containing a large amount of feldspar and biotite (*i. e.*, arkose). It was deeply buried beneath the surface and subjected to the same compressive forces that have produced all gneisses,

*See Geological Map of Conn., Bull. No. 7, Conn. Geol. and Nat. Hist. Surv.

but in this case the pressure was more extreme than in any specimen previously described. The geological evidence points to at least two such periods of great compression in western Connecticut since Cambrian times. The Becket gneiss must have been subjected to both these actions, and had, moreover, previously to the Cambrian, suffered from compression and metamorphism, of which we have no definite record. When a rock has been subjected to a number of such disturbances, it becomes exceedingly difficult if not impossible to determine its original character; and in the present instance it is only possible to state that it was probably derived from a feldspathic rock, either igneous or sedimentary.

The defects of the Becket gneiss as a building stone are practically the same as those of the Putnam gneiss (see page 179), and it is not used in Connecticut save for such work as foundations.

THE SCHISTS.

The schists include all closely foliated crystalline rocks. Mineralogically, they are distinguished from the gneisses by the fact that the feldspar is in general small in amount and inconspicuous. The word schist is derived from a Greek adjective meaning cloven, and signifies that the rock cleaves readily along the planes of foliation or *schistosity*. This cleavage or foliation is much better developed in schists than in gneisses. Schists may be the result of the metamorphism of sedimentary rocks containing little or no feldspar (*i. e.*, quartzose sandstone and shale), or of the extreme metamorphism of feldspathic rocks chiefly igneous, whereby the original feldspar is destroyed and replaced by other minerals, chiefly mica, epidote, and quartz. If basic igneous rocks undergo metamorphism, other minerals besides feldspar may change; thus pyroxene, as shown in gabbro (Specimen No. 19), is changed to hornblende. The latter may in turn be converted into chlorite where hydration is the principal factor of alteration. Schists are commonly named according to the most conspicuous minerals they contain; for example, mica schist, hornblende schist, and chlorite schist.

Other important minerals that result from metamorphism are garnet, staurolite, cyanite, sillimanite or fibrolite, andalusite,

diopside, tremolite, actinolite, and graphite, all of which may aid in determining the original character of the rock. Varieties of schist derive special names from these accessory minerals; for instance, garnetiferous mica schist. Garnet and staurolite are silicates of iron and alumina, and signify that a schist containing them must originally have been a rock rich in those constituents; that is, an impure clay or shale. Cyanite, fibrolite, and andalusite, all silicates of alumina, show similarly that the original rock must have been a clay or shale without much iron. Tremolite and diopside, both silicates of lime and magnesia, show that the original rock must have been a magnesian limestone or a calcareous sandstone or shale, according to the other minerals present. Actinolite, like tremolite, shows the presence of lime and magnesia, and, in addition, shows that the original rock contained an appreciable amount of iron. Graphite, or crystallized carbon, proves that the original sediment contained organic matter, as is the case, for example, in black shale.

SCHISTS OF IGNEOUS ORIGIN.

No. 29. Hornblende-Biotite Schist.

Rockville, Vernon, Conn.

Biotite schist is a foliated crystalline rock composed essentially of biotite and quartz, usually with a subordinate amount of feldspar. If hornblende is also present in noteworthy amounts, the rock becomes a hornblende-biotite schist.

The hornblende-biotite schist here described is a variation of the extensive and variable formation which has been named Glastonbury granite-gneiss.*

This formation extends from the Massachusetts line southward to Portland, forming the western boundary of the Eastern Highland, as far as Glastonbury. The hornblende-biotite schist occurs along its western edge, and is well developed at Rockville, where the present specimen was taken.

The rock is black in color and is spotted with numerous yellowish white rounded areas (*augen*). The schistose structure is very well developed. The rock has a notably high specific

*For a general description of the Glastonbury granite-gneiss, see Bull. 6, Conn. Geol. and Nat. Hist. Surv., pp. 115-120, 1906.

gravity, due to the abundance of biotite, hornblende, and epidote, minerals of decidedly higher specific gravity than the feldspar and quartz of granite.

The visible minerals are feldspar (plagioclase), biotite, a subordinate amount of hornblende, and epidote. The plagioclase has been thoroughly granulated by the pressure to which it has been subjected, and cannot possibly be distinguished from quartz without the aid of a microscope. It is impossible with only a lens to state whether any quartz is present or not.

The plagioclase occurs in the rounded areas, or "augen,"* and also in small flattened lenses between layers of biotite. The biotite, as in the gneisses, occurs in sheets of small flakes along the foliation planes. It presents no further noteworthy characteristics. The hornblende may not be readily recognized. It is very subordinate to the biotite, which commonly conceals it. It is black in color and has a good cleavage, though not nearly as perfect as that of biotite, nor has it so brilliant a surface. It also lacks the flaky character. The hornblende is most easily observed on the edges of the specimen, where it can be readily distinguished from the thin flakes of biotite. The epidote occurs in minute yellow grains, scattered evenly throughout the rock, and also in the augen, imparting to them their yellowish color.

All the features above mentioned have special significance. The schistose and highly granulated character of the feldspar has been explained in previous sections, and needs no further comment. The high specific gravity and black color suggest a presumption of igneous origin, since sedimentary rocks are rarely of high specific gravity, the heavy minerals contained in the more basic igneous rocks being largely decomposed before they can be transported and deposited to form sediment. It is altogether probable that the rock is of igneous origin.

The epidote was probably formed in the following manner. The plagioclase feldspar, a silicate of lime, soda, and alumina, was acted upon by heated water under pressure, and was partially decomposed; the lime, alumina, and some silica, uniting with some iron, formed the secondary mineral, epidote, while the remainder of the silica was removed in solution or recrystallized

*From the German, meaning "eyes". Named from the eye-like aspect of certain phenocrysts in foliated rocks.

as quartz. Thus the small yellow crystals of epidote are now found scattered all through the rock, replacing, in part, the original plagioclase. The water also attacked the black minerals present, and extracted a portion of their iron, which contributed to form the epidote. Epidote, therefore, represents a reaction between dissolved products of plagioclase and a black, iron-bearing mineral. The soda from the original plagioclase may have gone partly to form the hornblende, but was more probably removed in solution. Whether biotite and hornblende were originally present, it is impossible to say. Both may have been original, or both may have been derived by metamorphism, since hornblende may have replaced original pyroxene and taken up soda from the decomposed plagioclase. The biotite may have been derived from either pyroxene or hornblende. Biotite, from its great abundance, may be partly original and partly secondary. The changes are undoubtedly complex, and, on the evidence afforded by hand specimens, can only be conjectured. A thorough microscopic study and chemical analysis of the rock might afford grounds for more definite conclusions.

This rock, owing to the ease with which it splits along the foliation planes, is easily quarried into flat blocks and slabs, and has met with considerable local use in the walls and foundations of buildings. Its dark color and lack of toughness detract from its value and prevent a more extensive use.

No. 30. Milford Chlorite Schist.

Savin Rock, Orange, Conn.

Chlorite schist is a foliated rock in which chlorite is the most prominent mineral to the unaided eye, although quartz and other minerals, mostly secondary, are seen when the rock is examined under the microscope.

The Milford chlorite schist is typically developed in the town of Milford, along the shore of Long Island Sound, and passes northward in a narrowing band through Orange and the western corner of New Haven, into Woodbridge, where it wedges out.

This rock is so strongly foliated as to be almost slaty in character. The light grayish green color is due to the mixture of chlorite, a dark green mineral, with microscopic grains of quartz, magnetite, and other minerals. No other minerals besides

chlorite are visible to the naked eye, except limonite, which may appear as rusty stains along the foliation planes. Chlorite is a very soft mineral and may be scratched by the thumb-nail. It develops usually in minute scales or flakes, and when abundant in schist causes the foliation to be very strongly marked.

Chlorite is a secondary mineral, a hydrous silicate of alumina, magnesia, and iron, produced by the action of heated waters upon biotite, hornblende, or pyroxene. Its presence in so great abundance must signify that the original rock contained a large amount of one or more of these minerals; that is, it was a basic rock. The highly developed foliation indicates that this basic rock suffered extreme compression. While the pressure was being exerted the chlorite was developed, and wrapping its flakes around the other minerals, whatever they may have been, has completely hidden them from view. The evidence obtained by a study of the region in which this formation occurs shows that the original rock was a diabase generally similar to Specimen No. 20. Remnants of the diabase still exist in some outcrops, and are seen to change gradually into the highly foliated chlorite schist. Apparently the pressure was not quite sufficient, or long enough continued, to alter the entire rock formation.

Chlorite schist has been used, though to a very small extent, as a green roofing slate,* for which it may serve well when the foliation is exceptionally regular. Most chlorite schist, however, as in the present instance, is too full of cracks and flaws to be useful as slate. There are rare instances where the schist has been used for building material; but the softness and weakness of the stone prevent extensive use.

SCHISTS OF SEDIMENTARY ORIGIN, AND QUARTZITE.

No. 31. Poughquag Quartzite.

North Canaan, Conn.

Quartzite, as the name implies, is a rock consisting essentially of quartz, with no other minerals present in noteworthy amount. It differs from a quartzose sandstone in containing practically no pore space, the porosity having been destroyed either by the filling of the pores with secondary silica deposited from per-

* E. C. Eckel: Jour. Geol., vol. XII, pp. 15-24, 1904.

colating water, or by the crushing and recrystallization under pressure of the original quartz grains, which so readjusted themselves as to obliterate the pore space and diminish the original volume of the rock. The Poughquag quartzite was, largely at least, formed in the latter way. The formation is named from a place in eastern New York where it occurs in typical form, and was studied previously to the study of the Connecticut localities. The quartzite occurs in several rather small isolated areas in the northwestern and western part of Connecticut, shown on the geological map of Connecticut.*

The rock is a dense mass composed almost entirely of quartz grains. Its color varies from nearly white to buff. The buff color is caused by numerous minute flakes of brown mica, disseminated through the rock, the depth of color varying with the amount of mica. On weathered surfaces, the rock is dotted over with rusty spots, due to the decomposition of the mica. The mica is sometimes sufficiently abundant along certain planes to give the rock the character of a quartz schist; but this is not usual. Where mica is present, it is commonly developed in the original bedding planes. Foliation planes distinct from the bedding planes have not been developed in these rocks as in rocks which are softer and more readily mashed by pressure.

In the Cambrian, the earliest division of the Paleozoic eon, the Poughquag formation was deposited as a beach and shallow water sand off the shore of an ancient land, consisting in this region of the Becket gneiss. This deposit was later more deeply submerged, and covered by accumulations of calcareous débris from the skeletons of marine animals, or by deposits of clay and sand. Later it was consolidated into sandstone; and, when the period of metamorphism supervened, this sandstone was compressed and recrystallized into quartzite. Its present exposure, as in the case of the other metamorphic rocks, is the result of long-continued erosion of the overlying formations.

Quartzite, owing to its extreme hardness and dense texture, is in general an undesirable and difficult stone to quarry; and, consequently, is rarely used. The Poughquag quartzite is no exception to the rule.

*Bull. No. 7, Conn. Geol. and Nat. Hist. Surv., 1906.

No. 32. Plainfield Quartz Schist.

South Killingly, Killingly, Conn.

Quartz schist differs from quartzite in possessing a pronounced foliation. There is usually a small amount of mica, or occasionally some other mineral, as amphibole or pyroxene, along the foliation planes. It is, in other words, midway in composition between a quartzite and a mica schist. Its chief mineral is quartz, but there is sufficient mica to develop the foliated or schistose structure; hence the name quartz schist.

The Plainfield quartz schist forms a narrow band extending from Massachusetts southward across the northeast corner of Connecticut, through the towns of Thompson, Putnam, Killingly, Plainfield, and Griswold, while an isolated area lies across the boundary between Voluntown and North Stonington, at Pendleton Hill.

The character of the rock varies somewhat in color and composition at different localities, but it is typically exposed in Plainfield. Here the mica is well developed. At Pendleton Hill the rock closely approaches quartzite in character. At South Killingly, where the specimens were collected, diopside (a pyroxene) is present and mica is absent, but the schistose structure is well shown along the broad surfaces. It cannot be detected, however, on the transvere fractures, and the rock as seen on those surfaces can hardly be distinguished from a quartzite. The quartz occurs in very fine grains, and presents a sugary or granular character, which has been developed, as in the gneisses and schists previously described, by compression. The diopside forms small, pale green, needle-like crystals, which lie along the foliation planes, generally in nearly parallel directions. They are not broken, and could not have existed before the rock was subjected to the pressure which granulated the quartz. Diopside is composed of silica, magnesia, lime, and a little iron. Its presence indicates that the original sediment was a sand which contained small amounts of these constituents. When the rock was subjected to metamorphism, the small amounts of lime, magnesia, and iron united with a proportionate amount of silica from the quartz, and formed the small diopside crystals, which grew in the direction of least pressure; that is, along the foliation planes.

The history of this rock, other than the development of the diopside, is similar to that of the quartzite (Specimen No. 31). Like quartzite, it is little used as a building stone. Its more schistose structure, however, enables it to split into thin slabs, which may be used as flagstones.

No. 33. Orange Phyllite.

Derby Trolley Cut, Orange, Conn.

Phyllite is a schistose rock midway between slate and mica schist in character. The thin cleavage plates, almost plane, often so closely resemble those of a true slate that the rock is called mica slate. It is usually not completely crystalline, and so differs from a true mica schist. The name phyllite, derived from the Greek word for leaf, is given to denote the thin, leafy layers into which the rock readily splits.

The Orange phyllite extends in a north-northeast belt over a distance of about twenty miles, from the town of Stratford on Long Island Sound through parts of Milford, Orange, Huntington, Derby, Ansonia, and Woodbridge, and ends in Bethany along the border of the Central Lowland. The belt is widest and best developed at Orange, and gradually narrows towards the northeast and southwest.

The Orange phyllite is a soft, highly foliated, dark gray rock. The only visible mineral, besides the rusty stains of limonite, is white mica in extremely fine flakes, a form of muscovite which is known by the name of sericite. The flakes of sericite are so abundant and well pressed together that they present an apparently continuous surface along the foliation planes of the rock. The gray color is due to included impurities which cannot be determined from examination by the eye alone. They may be finely divided grains of carbonaceous matter such as occur in black shale (Specimen No. 15); or they may be in part fine scales of chlorite. Microscopic study and chemical analysis are necessary to determine accurately these and other minerals, especially quartz and minute garnet grains, which in all probability are present but are concealed by the scales of muscovite.

The specimen shows, besides the foliation proper, wrinklings over the foliation surface in two oblique directions. In one set

of these the wrinkles are very fine and numerous; in the other they are larger and fewer. The second set greatly weakens the rock, so that it often splits along the wrinkle instead of along the foliation, imparting a fissile character to the rock. The finer wrinkles often show S-shaped curves between the larger wrinkles, the ends of which bend towards the direction of the larger wrinkles. The appearance suggests that the rock had suffered slight differential movements in the direction of the larger wrinkles, and that the finer ones were dragged in this direction, so as to develop the curved outline.

The abundance of mica and the dark color of the rock lead to the belief that it was formerly a black carbonaceous shale, which was at some period subjected to great pressure and some heat. These forces were sufficient to cause partial crystallization of the impure clay of the shale into mica, and to develop the finely foliated structure; but they were not great enough to cause all the constituents of the shale (as, notably, the carbon) to crystallize, and consequently left the rock in a semicrystalline state. Greater heat and pressure would have produced complete crystallization and developed a true mica schist, such as the three specimens next described (Specimens Nos. 34, 35, 36a). After the foliation had been developed pressure was exerted in a new direction oblique to the foliation and acted in such a way as to develop both sets of wrinkles and to curve the finer set as described above.

The soft, fragile character of phyllite renders it unfit for commercial use.

No. 34. Hartland (Hoosac) Schist.

Roaring Brook, Southington, Conn.

Specimens Nos. 34, 35, and 36a are fairly typical of mica schist — a highly foliated rock, in which mica is the most conspicuous mineral, but which contains also quartz and usually a few accessory minerals. Among the more common of the latter are garnet, staurolite, and fibrolite. The mica is usually the white variety (muscovite or the fine-grained form called sericite), but biotite may be present.

The Hartland schist extends from the towns of Hartland and Granby at the Massachusetts line southward along the

border of the Central Lowland to Wolcott, where it narrows and swings to the southwest, reaching Long Island Sound at Bridgeport and Fairfield. A separate belt extends southward from Litchfield to Newtown, and a small isolated area lies in the eastern half of Redding.

The Hartland (Hoosac) schist varies considerably in character, but the specimens here described are thought to represent the most abundant type. The rock is silvery white in color, owing to the closely interlocking grains of muscovite, is highly foliated, and presents along the foliation surfaces an excellent example of crumpling. The several layers have been crumpled into a succession of waves.

The minerals present are, besides muscovite, quartz, biotite in small amounts, garnet, staurolite, and an inconspicuous quantity of cyanite. The quartz, best seen on the narrow surfaces of the specimen, occurs in small but typical granulated lenses, and is completely hidden by the micas on the broad foliation surfaces. The biotite is so intimately interwoven with the muscovite that it is readily overlooked. The garnet is easily distinguished. It forms small crystals of twelve faces (dodecahedrons) or twenty-four faces (trapezohedrons), is dark to pale red in color, and very clear. The staurolite is much darker than the garnet and occurs in small prisms. In many instances two of these prisms have grown across each other, forming X-shaped (cruciform) twins. Cyanite, though commonly present throughout the formation, does not occur in the specimens, unless in microscopic crystals. It forms, where it does occur, light blue, blade-like prisms.

The Hartland (Hoosac) schist was formerly an argillaceous sandstone or shale. It contained, besides quartz and kaolin (hydrous silicate of alumina), a considerable amount of potash (in grains of undecomposed feldspar or mica), iron oxides (free or in undecomposed silicates), and a little lime and magnesia (either in undecomposed silicates or as carbonates). Like the other rocks of the Connecticut Highlands, it was subjected to enormous horizontal compression acting in a generally east-west direction, which caused it to recrystallize completely. Part of the potash present united with part of the kaolin to form muscovite; potash, iron oxide, and magnesia united with kaolin to form biotite;

iron oxide and magnesia united with kaolin to form garnet and stanrolite; any remaining kaolin was crystallized into cyanite; and the quartz was crystallized into the granular lenses. As a result the whole rock became highly foliated, the folia assuming nearly vertical positions regardless of the original bedding of the rock. After, or during, this metamorphism, the schist was subjected to a smaller compression which acted in a north-south direction and produced the crumpling seen on the foliation surfaces.

Mica schists, owing to their softness and frequent contortion or crumpling, are not well fitted for building purposes; but the Hartland (Hoosac) schist was quarried to furnish stone for the New Britain reservoir dam on Roaring Brook in Southington. The same rock has been worked in Roxbury and Washington for the exceptionally large garnets it contains.

No. 35. Berkshire Schist.*

Salisbury, Conn.

The Berkshire schist occurs in several detached areas in the western and northwestern parts of the state. It extends westward into New York and northward into Massachusetts, deriving its name from Berkshire County, where it is typically developed.

The rock in its main characters is similar to the Hartland schist. It is highly foliated, consists chiefly of quartz and fine silky white mica (sericite), and contains numerous crystals of garnet and staurolite. The quartz exists in small flattened grains, and is mostly hidden by the enveloping mica. The latter is composed of many minute flakes, so closely laid together as apparently to form a continuous sheet. The garnets form well shaped dodecahedrons, or twelve-faced crystals, and are sometimes as much as half an inch in diameter. Close examination shows the mica flakes curving around the garnet crystals. The staurolites are recognized by their prismatic form and darker color. They vary in size from minute crystals to prisms an inch long. Cruciform or X-shaped twinning (see page 62) is common. Biotite may be present, but has probably been bleached

*Owing to the lack of fresh exposures, the specimens are more or less weathered and stained.

during the weathering of the rock, and cannot now be distinguished from the iron-stained sericite.

Specimens of the Berkshire schist do not exhibit the fine crumplings of the Hartland schist, but contortions too large to show in hand specimens are commonly exposed on the rock outcrops.

The geological history of the Berkshire schist is practically the same as that of the Hartland schist (Specimen No. 34); that is, it was formerly an impure sandstone or shale, which by recrystallization during metamorphism became a mica schist, with the accessory minerals, garnet and staurolite.

The rock, owing to its soft and highly contorted character, has practically no value as a building stone, but may serve as a source of garnets.

Nos. 36A and 36B. Bolton Schist.

Vernon, Conn.

The Bolton schist forms a long narrow band extending in a south-southwest direction from Massachusetts almost across the east-central portion of the state. It lies mostly in Tolland and Middlesex counties. The town of Bolton, where the schist is typically developed and has been quarried, lies at about the center of the belt.

The Bolton schist is made up of two distinct varieties, which in some localities occur in alternating layers from one to several inches in thickness. These varieties are represented by Specimens Nos. 36a and 36b.

No. 36A. Muscovite Variety.

This is the more coarsely crystallized, and is a typical muscovite schist. Its description is generally similar to that of the two preceding specimens, Nos. 34 and 35. The wavy character along the foliation is irregular, and is evidently due to the presence of garnet and staurolite crystals, which have grown between the mica scales. These minerals are usually well developed and need no further description. Finely granular quartz lies in short flattened lenses parallel to the foliation. The specimens usually show a moderate amount of weathering, and are

stained along the planes of foliation by yellow films of limonite.

No. 36B. Quartzose Variety.

This is the more finely crystallized variety, and approaches a quartz schist in composition and structure. Its foliation surfaces are more nearly plane, appearing less flexed than those of the muscovite variety. The most abundant mineral is fine, granular quartz, through which fine scales of mica, both muscovite and biotite, are scattered in sufficient amount to develop a distinctly schistose character. Garnet in clear, well-formed, twenty-four-sided crystals (trapezohedrons) is the only other conspicuous mineral. Staurolite is very rare or entirely absent. The foliation surfaces are usually much more micaceous than the rest of the specimen. They may mark the passage of the quartzose into the muscovite variety, or may be mere films between quartzose layers. The quartzose rock nearly always splits along one of these films.

The Bolton schist has in general the same significant features as the Hartland and Berkshire schists. It was originally an impure clay or sand, later consolidated and greatly metamorphosed. The character of the minerals present shows the varying character of the original sediments. If the two types are compared, it is seen that the muscovite variety, with its large percentage of minerals containing alumina, must be regarded as derived from an impure clay or shale which held considerable potash and iron oxide; the quartzose variety must have been derived from a rather ferruginous clayey sand or shaly sandstone, since the quartz is accompanied by a minor amount of the aluminous minerals, mica and garnet. Where these varieties alternate in layers, there must have been an alternation of conditions during deposition of the original sediment: first the water must have been quiet, allowing the fine clay to deposit; then it became less quiet, so that fine sand and only a minor percentage of clay could be laid down.

The muscovite variety is not well adapted for commercial use, on account of its softness and the rather highly folded character of the rock. The quartzose variety is harder, and less folded when occurring in rather thick beds, and was much

quarried in former years for flagstone. Sidewalks in several Connecticut cities consist of this rock. The micaceous films cause the rock to split readily into thin slabs of suitable thickness; but the presence of mica and the granular character of the quartz weaken the resistance to abrasion, and the flagstones which have been long in use are not uncommonly seen with hollows worn in them.

CARBONATE ROCKS.

The metamorphic carbonate rocks are known as marbles, and consist either of crystalline calcite or dolomite, the first known simply as marble, the second as dolomitic marble. Commercially the name marble is extended to include any soft rock which takes a good polish, and hence may include not only limestones of various colors, but also serpentine. Mixtures of calcite and serpentine in varying proportions often occur. Marbles have many varying names based on color, texture, and other physical characters. Those of Connecticut, although rather limited in area, vary from pure white marbles, often dolomitic, to dark gray marbles whose color is due to graphite. All degrees of micaceous marbles are also encountered, due to the transitional passage of the Stockbridge dolomite formation into the overlying Berkshire schist. All degrees of coarseness in texture also occur, due to the local variations in the intensity of the metamorphism. The coarser varieties are valueless on account of their great friability, as are nearly all of the impure kinds on account of their unpleasing streakiness and somber colors. The result is that in a marble formation only a relatively small portion is suitable for architectural purposes. Yet such a relatively small portion may yield practically inexhaustible supplies of material. In collecting the specimens of Connecticut marbles, the pure type was omitted, and the tremolitic variety chosen instead, since it is identical in appearance with the pure marbles, save that it possesses in addition the crystals of tremolite.

No. 37. Stockbridge Tremolitic Marble.

East Canaan, North Canaan, Conn.

The Stockbridge marble, or dolomite, lies in several detached areas in the western part of the state. The two most important

are the irregular belt extending across the northwest corner through North Canaan, Canaan, Salisbury, and Sharon, and the narrow belt lying mostly in New Milford and Danbury. This marble was first studied in Massachusetts, and was named after the town of Stockbridge in that state.

The specimen taken is a white medium-grained crystalline dolomitic marble formed of crystal grains of the mineral dolomite. It is much softer than granite and similar rocks, and can be scratched easily by a steel knife-blade. The only conspicuous mineral besides dolomite is tremolite, which occurs in light colored flat prismatic crystals scattered through the rock. It is a silicate of magnesia and lime. A few specimens may show brown scales of the magnesian mica, phlogopite, which occurs occasionally but very irregularly.

Pure carbonate deposits originate chiefly by the accumulation of débris of shells, corals, and other skeletons of marine organisms, over the bottoms of shallow seas, either at a considerable distance from lands which supply sandy and muddy sediment, or closer to low-lying lands whose meager detritus is not sufficient to make the water muddy and mask the slow accumulation of the carbonate. The great amount of magnesium carbonate is an indication of considerable chemical reaction on the ancient sea bottom between magnesium salts in solution and the calcium carbonate of the recently accumulated strata.

In time, however, the conditions changed, much mud and some sand were swept seaward from the re-elevated lands to the east, and the Stockbridge dolomite became buried beneath a great thickness of detritus. Finally, granitic intrusions and horizontal mashing took place, the somewhat siliceous dolomite being metamorphosed into a marble often exhibiting tremolite crystals, called "dogs' teeth" by the quarrymen, and the overlying formation being metamorphosed into the Berkshire schist. The whole was forced by the horizontal compression into a complex system of mountain corrugations. Erosion working upon this mass has developed the present topography of open valleys where the readily soluble marble was exposed, and intervening hills and mountains where the Berkshire schist remains.

This rock has been quarried both in Massachusetts and in East Canaan, Conn., for marble, and the state capitol at Hartford

is built of the East Canaan stone. The chief use, however, of the rock is in the manufacture of lime. For this purpose it is broken into small blocks, and burned in kilns to drive off the carbon dioxide, and the burned product is packed in barrels for shipping. Dolomite affords a more slowly "setting" lime than does pure limestone, and, for many purposes, is more desirable on that account.

Chapter V.

PEGMATITES AND VEINSTONES.

PEGMATITES.

Pegmatite is the name given to very coarsely crystallized rocks, usually of granitic composition, and sometimes called giant granite. It always occurs in dikes or veins of varying width. The essential mineral constituents of the ordinary pegmatites are quartz and feldspar in varying amounts. Sometimes feldspar constitutes almost the entire mass; sometimes quartz is more abundant than feldspar, and, in extreme cases, is so abundant that the pegmatite dike grades into a pure quartz vein. In other words, pegmatites mark a perfect gradation from true igneous rocks on the one hand to pure quartz veins on the other, and a single vein may show the gradation perfectly. The most abundant accessory minerals are white and black mica; but many other minerals, especially gem minerals, may be present, such as tourmaline, beryl, and garnet. Most of the gems of commerce are obtained from pegmatite. As the formation of pegmatites is believed to be due to an aqueo-igneous action, they are intermediate, in origin as in mineral composition, between plutonic rocks and veinstones. The masses of pegmatite intersecting other rocks may therefore be called dikes or veins with about equal propriety.

No. 38. Pegmatite.

West Cornwall, Cornwall, Conn.

The principal localities where pegmatite has been quarried within the last few years in Connecticut are at South Glastonbury, Portland, and Haddam Neck. Other localities which have been worked in former times are in Middletown, Branchville, and Cornwall; but little or no work has been done very recently at these places. The veins vary from a few feet to a hundred feet or more in width, but the length of the outcrop is usually not more than ten to twenty times the width. The rock occurs very

abundantly over many parts of Connecticut, most of the gneisses and schists of the Eastern and Western Highlands being intersected more or less extensively by intrusions of pegmatite, varying from little lenses and thin streaks to great dikes.

The specimens were collected from a small vein one mile south of West Cornwall station. They show the feldspar and quartz in large crystals and in varying amount. The feldspar is easily distinguished by its whiteness, semi-opacity, and perfect cleavage. It generally forms well-defined, though not perfect crystals. The quartz occurs in large irregular masses and is recognized by its glassy appearance and gray to smoky color. As it was the last mineral to crystallize, it simply filled the interspaces among the other minerals and has no crystalline shape of its own.

The accessory minerals shown in all the specimens are muscovite (white mica) and biotite (black mica). A few specimens may show tourmaline and garnet, but these minerals are not plentiful and are irregularly distributed. The muscovite often occurs in distinct crystals, its shiny cleavage surface forming the base of a rudely six-sided prism. The biotite occurs in the same way, differing from muscovite only in color. The tourmaline when present forms black columnar crystals, generally showing longitudinal lines or striæ on its prismatic faces, and a shining irregular fracture somewhat resembling coal. The garnet forms small red translucent grains, which on close inspection are seen to be crystals with many faces. These crystals, if fully developed, would show twenty-four faces, but, owing to their generally distorted growth, these are only partly visible.

Pegmatite, as its mineral composition would imply, is closely related to normal granite. But the molten mass from which it crystallized contained an unusual amount of water, which increased greatly the fluidity of the mass, and allowed the crystals to grow to a great size, much as they do in an ordinary solution. It is thought, on good evidence, that granite in crystallizing sets free a considerable amount of water and other more or less volatile substances which form a very liquid residue. In connection with the consolidation of the granite, fissures are developed in it, either by shrinkage or by movements due to pressure, and the highly fluid mass forces its way upward through

these fissures into the already solidified granite and the adjacent rocks. The mineral substances crystallizing out of the water solution build up the pegmatic veins, but such veins are formed at a temperature not much below that of igneous intrusions.

Pegmatite has several uses. First, the feldspar, when white or nearly white in color, is useful in the manufacture of porcelain. The quartz is ground and used in manufacture of glass, wood finishers, and abrasives. White mica, when occurring in sufficiently large crystals and of sufficient purity, is useful as isinglass; and small fragments known as scrap mica are ground and used as an insulating material in electrical apparatus and for other purposes. Black mica is useless. Tourmalines, beryls, and garnets, when free from flaws, are valuable as gems.

VEINSTONES.

The intrusion of great igneous masses at several intervals in the Paleozoic eon into the Connecticut rock formations, and the orogenic movements accompanied by mashing and metamorphism, resulted in a greatly increased temperature and the saturation of the rocks with highly heated vapors. The latter were doubtless in part due to the original moisture in the sediments, and to the underground circulation of rain water, but also in part to emanations escaping from the molten igneous masses. Such heated vapors have the power of taking considerable rock material in solution and depositing it nearer the surface where the temperature is lower. The result is either the filling of fissures, giving true fissure veins; or a reaction with the walls, giving replacement deposits. Veinstones consequently belong to that division of metamorphic actions classified under the term *metasomatism,* meaning a change in the bodily composition of the rock mass, as distinguished from a mere mashing and recrystallization.

No. 39. Lantern Hill Quartz Rock.

Lantern Hill, North Stonington, Conn.

The term "Quartz Rock" is here used to denote a rock composed almost entirely of quartz, but neither a quartzite nor a vein quartz in the strictest sense. It is, however, closely re-

lated in structure and origin to quartz veins, as will be shown later.

The Lantern Hill quartz rock lies on the boundary between Ledyard and North Stonington in the southeastern part of the state. It forms the material of Lantern Hill and Long Hill, and covers an area a little over a mile long, and in most parts several hundred feet in width. It lies within the area of the Sterling granite-gneiss.

The Lantern Hill rock is a combination of many small parallel quartz veins separated by sheets of massive or granular quartz. This combination produces, for the most part, a hard, firm rock; but near the southern part of the area it is of very loose texture and crumbles under a light blow. The specimen is taken from this loose-textured variety which is of some commercial importance. The firmly consolidated rock is similar to the vein quartz which may be seen in any of the metamorphic formations.

The specimen illustrates the loose-textured rock, and also the natural sand into which the rock crumbles by weathering. The friable quartz is composed of well-formed crystals (six-sided prisms terminated by pyramids) scattered through a very finely granular rock. The quartz crystals vary in size from microscopic dimensions to an inch or more in length. Sometimes they line the walls of small cracks and form small quartz veins. This arrangement of crystals side by side resembles the teeth of a comb, and is known as *comb structure*. The cracks are in very many cases poorly defined, and the crystals appear in the specimen to have no definite arrangement.

If the finely granular part is breathed upon, it will give strongly the peculiar odor of clay, which proves that clay is present though not distinguishable from the finest crystals and grains of quartz. Close inspection may, or may not, disclose a few fine scales of mica, sometimes silvery white, sometimes pale greenish in color — the variety known as sericite. Some of the specimens may not show it, though it is thinly distributed throughout the mass of the rock.

The natural powder is significant in showing that a rock composed mostly of the hard, durable mineral, quartz, may, under the special conditions mentioned below, be greatly de-

ficient in cohesive strength, owing to the lack of cementation of the individual particles.

The history of this rock can be only partially appreciated from the description. The rock was originally a granite which had been broken into thin layers or sheets by a large number of parallel fractures or *joints,* extending in a north-south direction. These joints were then filled from below by highly heated waters carrying quartz in solution. The water filled not only the main parallel joints, but also the innumerable minor cracks which traversed the sheets of granite in all directions. The feldspar was decomposed by the water, forming kaolin and mica (sericite). The cavities — both those resulting from the fractures, and those left by the decomposition of the feldspar — were filled partially or completely by the quartz deposited from the water. Where this filling was complete, the rock, originally granite, became hard solid quartz; where it was incomplete, the numerous cavities, and the relatively large amount of soft kaolin, left the rock in a friable condition as illustrated by the specimen.

No. 40. Siderite.

Mine Hill, Roxbury, Conn.

Siderite is the carbonate of iron, an ore of some commercial importance, though less abundant than magnetite, hematite, and limonite. It is light to dark brown in color, and may be cleaved in three oblique directions. Cleavage faces have the shape of a rhomboid, and blocks bounded by three pairs of cleavage planes have the form of a rhombohedron. It is similar in this respect to the lime and magnesia carbonates, calcite and dolomite, but it has a specific gravity decidedly higher than that of calcite or dolomite. It is distinguished from limonite by its cleavage, although both minerals may be alike in color.

This specimen of siderite was collected from the well-known siderite vein at Roxbury, Conn. The vein is said to average about eight feet in width, and has been opened for upwards of a mile on the southeast slope of Mine Hill. The position of the vein can be found only in a few places where it is marked by old mine shafts. The vein itself has been worked out at these openings, and its character is shown only by the specimens in the old dumps.

The rock consists chiefly of brown massive siderite, presenting many shining cleavage surfaces, and enveloping long, white six-sided crystals of quartz. These quartz crystals grew nearly at right angles to the walls of the vein. Exposure on the dump has caused a darkening of the surface of the siderite by the development of films of the brown hydrous oxide, limonite.

The origin of this siderite vein, like that of the quartz rock just described, dates back to the time when the enclosing rock, a granite-gneiss, was broken by fissures. One or more of these fissures were filled by water carrying iron bicarbonate and silica in solution, from which the iron crystallized as siderite and the silica as quartz. The long, pencil-like form of the quartz crystals is very significant. Both siderite and quartz crystallized together, but the siderite was more abundant, and the quartz crystals were enclosed on all sides by siderite, except where the base of the prism was in contact with the solution. The crystals, accordingly, could not increase in diameter, and material could be added only in the direction of growth.

This vein was formerly worked for iron ore, but its small size and the difficulty of mining it, in comparison with the enormous and more easily worked deposits of the Lake Superior region, prevent it from paying at present. It has not been worked for over thirty years.

INDEX

Arabic numerals refer to pages; Roman numerals preceded by the letter T refer to tables.

Actinolite, 59, T III.
Adobe, 98, T V.
Albite, 39, T I.
Alkali incrustations, 110.
Amphibole, 41, T I.
Amphibolite, 123, T IV, T VI.
Amygdaloid, 170.
Anamorphism, conditions of, 111.
  definition of, 27, 28.
  relations of, 57.
Andalusite, 60, T III.
Andesite, 84, T IV.
Anhydrite, 53.
Anorthite, 39, T I.
Anthracite, 109.
Aplite, 86, T IV.
Aragonite, 50.
Argillaceous limestone, 100, T V.
Arkose, 98, 156, T V.
Atmosphere, origin of, 17.
Augite, 41, 42, T I.

Basalt, 83, 84, T IV.
  Triassic, 169.
Basaltic obsidian, 82, T IV.
Beach pebbles, 150.
Becket gneiss, 180.
Benvenue quarry, Middletown, 175.
Berkshire schist, 191.
Biotite, 41, T I.
Bituminous coal, 108.
Black shale, 158.
Bolton, 192.
Breccia, 76.
  of igneous origin, 76, 80, T IV.
  talus, 97.
Branford, 158, 162.
Bristol, 176.
Bristol granite-gneiss, 176.
Brown coal, 108.

Calcareous rocks, 99, 194.
Calcareous tufa, 101, T V.
Calcite, 50, T II.
  cement, 101.
  vein, 101.
Caliche, 101.
Carbon dioxide, expulsion of, from rocks, 112.
  origin and activities of, 107.
Carbonaceous rocks, 105, T V.
Carbonates, origin of, 51.
Cement calcite, 101, T V.
Cement quartz, 45.
Cement rock, 100, T V.
Chert, 104, T V.
Chlorite, 48, T II.
Chlorite schist, 130, T VI.
  Milford, 184.
Classification, principles of, 77, 94, 113.
Classification of igneous rocks, 79.
Classification of metamorphic rocks, 119.
Classification of sedimentary rocks, 94.
Clay, brick, 99.
  fire, 99.
  of Glacial period, 146.
  pure, 99.
Clay concretions, 148.
Cleavage, crystalline, 33.
  flow, 121.
  fracture, 121.
  of minerals, 33.
Climate as a factor in rock decay, 46.
Coal, 106.
  relation of, to organic cycle, 107.
Coal series, 106, T V.
Color and streak, 34.
Compact limestone, 100, T V.

Composition of earth crust, 21, 22.
by minerals, 36.
Concretions, clay, 148.
definition and origin of, 93.
Conglomerate, 97, 154, T V.
Consanguinity of rocks, 68.
Coquina, 100, T V.
Cornwall, 138, 180, 197.
Crystalline schists, 119, 121, T VI.
Crystallization, process of, 73.
Cyanite, 61, T III.

Danbury granodiorite-gneiss, 173.
Decomposition of rocks, 47.
Derby, 171.
Devitrification, 81.
Destructive metamorphism, 45.
Diabase, 86, T IV.
Triassic, 167.
Diatom earth, 103, T V.
Differentiation of magmas, 67.
Diorite, 88, T IV.
Disintegration of rocks, 47.
Dolerite, 87.
Dolomite, 52, 103, T II, T V.
Drusy quartz, 38, T I.
Durham, 158.
Dynamic metamorphism, 116.

East Canaan, 194.
East Lyme, 150, 161.
Elements, association of, 26.
chemical classification of, 22.
common in earth's crust, 21.
definition of, 20.
Elmwood, 148.
Epidote, 62, T III.
Eruptive breccias, 76.
Evaporation products, 110, T V.
Explosive breccias, 76.
Extra-telluric crystallization, 73.

Fair Haven, 156.
Feldspar, 38, T I.
Felsite, 83, T IV.
Ferrous carbonate, 53.
Flint, 105, T V.
Flow breccias, 76.
Flow-and-plunge structure, 93.
Fool's gold, 44.
Fusing points of magmas, 71.

Gabbro, 88, T IV.
Gabbro-diorite, Preston, 165.
Garnet, 58, T III.
Garnet and magnetite sand, 151.
Geyserite, 104, T V.
Giant granite, 88.
Glacial drift, 97, 141, T V.
Glaciated pebble, 143.
Glasses, volcanic, 81.
Gneiss, 119, T VI.
Becket, 180.
Putnam, 178.
Gneisses derived from sedimentary rocks, 120, 178, T VI.
Gneisses derived from igneous rocks, 119, 171, T VI.
Gneisses of unknown origin, 120, 180, T VI.
Granite, definition of, 87, T IV.
graphic, 88.
Stony Creek, 162.
Thomaston, 159.
Westerly, 161.
Granite-gneiss, 120, T VI.
Bristol, 176.
Maromas, 175.
Prospect porphyritic, 171.
Stony Creek, 174.
Granodiorite-gneiss, Danbury, 173.
Graphite, 64, T III.
Grit, 97, T V.
Ground-mass, definition of, 70.
Guilford, 174.
Gypsum, 52, 56, T II.
conditions of deposit of, 110.

Halite, 56, T II.
Hamden, 146, 152.
Hardness, scale of, 32.
Hartland schist, 189.
Hematite, 55, 56, 127, T II.
Hoadley Point, 174.
Hoosac schist, 189.
Hornblende, 41, 42, T I.
Hormblende biotite schist, 182.
Hornblende schist, 123, T VI.
Hornblendite, 89, T IV.
Hornfels, 126, T VI.
Hydraulic limestone, 100, T V.

Igneous rocks, 65, 159.
chemical variations of, 65.
classification of, 79.
classification of, by mineral composition, 65.
Infusorial earth, 103.
Intra-telluric crystallization, 73.
Iron ores, 53, 109, T II, T V.
chemistry of accumulation, 54.
metamorphic, 127.

Jasper, 38, 128.

Kaolin, 138.
as a basis for soils, 48.

Kaolin, impurities of, 48
tests for, 48.
Kaolinite, origin of, 46, 47, T II.
Katamorphism, definition of, 45.
Killingly, 187.

Lantern Hill, 199.
Lantern Hill quartz rock, 199.
Lake Saltonstall, 158.
Lavas, 82.
Lignite, 106, 108, T V.
Lime-magnesia metamorphic rocks, 127.
Limestone, 99.
Limonite, 54, 55, 139, T II.
Lithographic limestone, 101, T V.
Lithology, definition of, 17.
use of, 19.
Loess, 98, T V.

Magma, definition of, 17.
Magmatic differentiation, 67.
Magnetite, 44, 127, T I.
weathering of, 45, 46.
Magnetite and garnet sand, 151.
Marble, 119, 124, T VI.
Stockbridge tremolitic, 194.
Marcasite, 44.
Marl, 100, T V.
Maromas granite-gneiss, 175.
Matrix, definition of, 70.
Meriden, 169.
Metamorphic cycle, 112.
Metamorphic rocks, 111, 171.
classification of, by origin, 118.
hydrothermal, 128, T VI.
hydrous, 129, T VI.
mixed types, 128.
Metamorphism, conditions of, 111, 116.
contact, 116.
dynamic, 116.
hydrothermal, 117.
hydrous, 129.
regional, 116.
static, 117.
thermal, 117.
Mexican onyx, 102.
Mica, 40, T I.
Mica schist, 122, T VI.
Microphanerites, definition and occurrence of, 85, T IV.
Middletown, 175.
Milford chlorite schist, 184.
Mine Hill, 201.
Mineral composition of earth's crust, 36.
Minerals, cleavage of, 33.
meaning of formulas of, 29.
Minerals, methods of identification of, 31
physical nature of, 30.
Monroe, 173.
Mudstone, 98, T V.
Muscovite, 41, T I.

New Haven, 141, 143, 144, 146, 156, 167.
Niantic, 150, 161.
North Canaan, 194.
North Stonington, 199.
Novaculite, 99, T V.

Obsidian, 82, T IV.
Olivine, 43, T I.
Oolitic limestone, 102, T V.
Opal, 38, T I.
Orange, 151, 184, 188.
Orange phyllite, 188.
Ore Hill, 139.
Orthoclase, 39, T I.
Oxides in earth crust, 22.

Parallel structures of igneous rocks, 75.
Peat, 106, 108, 152, T V.
Pegmatite, 197.
definition of, 87, T IV.
dikes of, 72.
Peridotite, 89, T IV.
Perlite, 82, T IV.
Petrographic provinces, 67.
Petrography, definition of, 18.
Petroleum series, 109, T V.
Petrology, definition of, 18.
Phanerites, definition of, 87.
Phyllite, 122, T VI.
Orange, 188.
Pitchstone, 82, T IV.
Plagioclase, 39, T I.
Plainfield quartz schist, 187.
Plaster of Paris, 53, T II.
Pleistocene formations, 137.
Porphyries, usage of names, 85.
Portland, 154, 157.
Potassium minerals, 57.
Poughquag quartzite, 138, 185.
Preston, 165.
Preston gabbro-diorite, 165.
Prospect porphyritic granite-gneiss, 171.
Pumice, 82.
Putnam, 178.
Putnam gneiss, 178.
Pyrite, 44, T I.
Pyroxene, 42, T I.
Pyroxenite, 89, T IV.

Quartz, 37, T I.
vein, 105.
weathering of, 45.
Quartz rock, Lantern Hill, 199.
Quartz schist, Plainfield, 187.
Quartzite, 125, 128, T VI.
Poughquag, 185.

Recent formations, 137.
Red shale, 157.
Residual materials, 137.
Rhyolite, 83, T IV.
River gravel, 144.
Roaring Brook, Southington, 189.
Rock glasses, 81.
Rock salt, 56, 110.
Rocks, classification of, 27.
definition of, 17.
disintegration of, 47.
weathering of, 45.
Rockville, 192.
Roxbury, 201.

Salisbury, 139, 191.
Salt, origin of, 40.
Saltonstall, Lake, 158.
Sand, Glacial period, 146.
Sandstones, 97, T V.
Savin Rock, 151, 184.
Shale, 98, T V.
Sharon, 138.
Schist, Berkshire, 191.
Bolton, 192.
chlorite, 130, 184.
Hartland, 189.
Hoosac, 189.
hornblende, 123.
hornblende biotite, 182.
mica, 122.
Milford chlorite, 184.
Plainfield quartz, 187.
quartz, 123, 187.
Schists, crystalline, 121, 181.
various minor, 124, T VI.
Scoria, 82, T IV.
Sea salt, origin of, 56.
Sedimentary rocks, structures of, 92.
textures of, 90.
Serpentine, 49, T II.
Serpentine rocks, 130, T VI.
Siderite, 53, 55, 201, T II.
Siliceous fillings, 105.
Siliceous sinter, 104.
Sillimanite, 61, T III.
Slate, 121, T VI.
structure of, 114.
South Killingly, 187.
Southington, 189.

Stalactites, 102.
Stalagmites, 102.
Staurolite, 62, T III.
Stevenson, 173.
Stockbridge tremolitic marble, 194.
Stony Creek, 162.
Stony Creek granite, 162.
Stony Creek granite-gneiss, 174.
Structures, amygdaloidal, 75.
concretionary, 93.
cross-bedded, 93.
definitions of, 74.
fissile, 114.
flow, 75.
fragmental, in igneous rocks, 76.
geodic, 74.
gneissoid, 115.
injected, 75.
laminated, 92.
massive, 76, 92.
obliquely bedded, 93.
of igneous rocks, 74.
of metamorphic rocks, 114.
of sedimentary rocks, 92.
perlitic, 75.
pumiceous, 74.
schistose, 115.
scoriaceous, 74.
shaly, 92.
spherical, 74.
spherulitic, 75.
stratified, 92.
thick-bedded, 92.
thin-bedded, 92.
vesicular, 74.
Syenite, 88, T IV.

Tachylite, 82, T IV.
Talc, 49, T II.
Talc rocks, 130, T VI.
Talus breccias, 97, T V.
Textures, aphanitic, 69.
brecciated, 91.
clastic, 90.
conglomeratic, 91.
definitions of, 69.
felsitic, 69.
glassy, 69.
granitic, 70.
gritty, 91.
morainic, 91.
of igneous rocks, 69.
of metamorphic rocks, 114.
of sedimentary rocks, 90.
oolitic, 92.
origin and significance of, in igneous rocks, 70.
pegmatitic, 70.

Textures, porphyritic, 70
sandy, 91.
Thomaston, 159.
Thomaston granite, 159.
Till, 97, 141.
Tillite, 97.
Topography as a factor in rock decay, 46.
Tourmaline, 63, T III.
Trachyte, 83, T IV.
Trap, 84, 86, T IV.
Travertine, 101, T V.
Tremolite, 59, T III.
Tremolitic marble, 194.
Triassic basalt, 169.
Triassic conglomerate, 154.
Triassic diabase, 167.
Triassic sandstone, 156.
Triassic shale, 157, 158.
Tripoli, 103.
Tuff, 80, T IV.
Vein quartz, 105.
Veinstones, 197, 199.
Vernon, 192.
Vesicles in basalt, 170.
Vesicular structure, 74.
Viscosity of magmas, 71.
Weathering of rocks, 45.
Whetstone, 99, T V.
West Cornwall, 138, 180, 197.
West Hartford, 148.
Westerly, R. I., 161.
Westerly granite, 161.
Westville, 141, 143, 144, 146.

Table I.

TABLE I.—COMMON MINERALS OF IGNEOUS AND METAMORPHIC (ANAMORPHIC) ROCKS.

NAME.	CHEMICAL COMPOSITION.	PHYSICAL PROPERTIES.				REMARKS.
		Hardness.	Cleavage.	Color.	Streak.	
Quartz (many varieties).	SiO_2.	7.	None.	Colorless or light-colored. Commonly light gray or smoky grains, or as white massive quartz.	White.	Vitreous luster. Transparent to translucent. Irregular fracture. Usually in irregular grains. In hexagonal prisms, when distinctly crystallized, with striations parallel to the base. Prisms capped by smooth-faced six-sided pyramids. Extremely resistant to decay.
Feldspar group.	Silicates of aluminum, and potassium, sodium, or calcium, with no iron or magnesium.	5-6.5	One perfect; one fair.	.....	White.	Orthoclase and plagioclase can often be distinguished only by chemical analysis or polarizing microscope.
Orthoclase.	$KAlSi_3O_8$.	6.	Cleavages at 90°.	White to light gray, buff, or pink.	White.	Potash feldspar. Common feldspar of granite. More resistant to decay than plagioclase.
Plagioclase.	xAlbite + yAnorthite.	5-6.5	Cleavages from 86°24′ to 85°50′.	White to dark gray.	White.	Lime-soda feldspar. Best cleavage plane generally striated. Common in rocks with much dark mineral.
Albite.	$NaAlSi_3O_8$.	6-6.5	Cleavages at 86°24′.	White.		
Anorthite.	$CaAl_2Si_2O_8$.	6-6.5	Cleavages at 85°50′.	Various.		
Mica group.	.....	2-3.	One perfect.	.....	White.	Soft, elastic plates or flakes with high luster.
Muscovite.	$H_2KAl_3(SiO_4)_3$.	2-2.5	One perfect.	Colorless or light-colored.	White.	Potash mica. Abundant in metamorphic rocks. Also found in granites.
Biotite.	$(H,K)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$.	2.5-3	One perfect.	Green, dark-brown to black.	White.	Iron-magnesia mica. Abundant in igneous rocks. Also frequent in metamorphic rocks.
Hornblende.	xCa $(Mg,Fe)_3Si_4O_{12}$ + $y(Mg,Fe)_2(Al,Fe)_4Si_2O_{12}$.	5-6	Prismatic; sections diamond-shaped.	Black.	Lighter than mineral.	Prismatic crystals, generally slender, Luster usually dull. Prismatic cleavage splintery, nearly perfect. Common in rocks with much black mineral.
Augite.	xCa $(Mg,Fe)(SiO_3)_2$ + $y(Mg,Fe)(Al,Fe)_2SiO_6$	5-6.	Prismatic; sections nearly square.	Black.	Lighter than mineral.	Chunky or prismatic crystals. In basic rocks. Usually difficult to distinguish from hornblende. Prismatic cleavage less perfect than in hornblende.
Olivine.	$(Mg,Fe)_2SiO_4$	6.5-7.	One fair cleavage; conchoidal fracture.	Olive-green.	Lighter than mineral.	Occurs in glassy grains, decaying rapidly upon exposure. Found in basic igneous rocks and a few impure marbles.
Magnetite.	Fe_3O_4.	6+	None.	Black.	Black.	Magnetic iron ore. Sparingly present in many rocks in small grains. Sometimes in larger masses.
Pyrite.	FeS_2.	6-6.5	Cleavage poor; fracture uneven.	Pale brass-yellow.	Greenish or brownish black.	Not an abundant mineral but one frequently occurring. Form is usually cubical. Rusts to limonite.

CKS.

REMARKS.
Vitreous luster. Transparent to translucent. Irregular fracture. Usually in irregular grains. In hexagonal prisms, when distinctly crystallized, with striations parallel to the base. Prisms capped by smooth-faced six-sided pyramids. Extremely resistant to decay.
Orthoclase and plagioclase can often be distinguished only by chemical analysis or polarizing microscope.
Potash feldspar. Common feldspar of granite. More resistant to decay than plagioclase.
Lime-soda feldspar. Best cleavage plane generally striated. Common in rocks with much dark mineral.
Soft, elastic plates or flakes with high luster.
Potash mica. Abundant in metamorphic rocks. Also found in granites.
Iron-magnesia mica. Abundant in igneous rocks. Also frequent in metamorphic rocks.
Prismatic crystals, generally slender, Luster usually dull. Prismatic cleavage splintery, nearly perfect. Common in rocks with much black mineral.
Chunky or prismatic crystals. In basic rocks. Usually difficult to distinguish from hornblende. Prismatic cleavage less perfect than in hornblende.
Occurs in glassy grains, decaying rapidly upon exposure. Found in basic igneous rocks and a few impure marbles.
Magnetic iron ore. Sparingly present in many rocks in small grains. Sometimes in larger masses.
Not an abundant mineral but one frequently occurring. Form is usually cubical. Rusts to limonite.

TABLE II.—MINERALS RESULTING FROM ROCK DECOMPOSITION (KATAMORPHISM).

NAME.	CHEMICAL COMPOSITION.	PHYSICAL PROPERTIES.				REMARKS.
		Hardness.	Cleavage.	Color.	Streak.	
Quartz.	SiO_2.	7.	None.	Colorless or light colors.	White.	Vitreous luster. Irregular fracture. Extremely resistant to decay.
Quartz sand.	....	.....	.....	.....	.....	Liberated from rocks by the decay of surrounding minerals.
Cement quartz.	.....	.....	.. ..	.....	.....	Siliceous cement from solution in hot or alkaline waters. In part set free by decay of silicates.
Kaolinite.	$H_4Al_2Si_2O_9$.	2-2.5	In fine flakes when crystalline, but mineral is usually amorphous and impure.	White when pure. Usually colored by iron oxide or carbonaceous compounds.	White.	Usually unctuous and plastic. From decay of aluminous silicates.
Chlorite group.	Basic hydrous silicates of aluminum, magnesium, and iron. Clinochlore an example.	2-2.5	Micaceous, but in fine-grained rocks often scaly or indistinct.	Green.	White.	Usually amorphous and forming green stains. From decay of iron and magnesium silicates. Numerous species not easily distinguished.
Clinochlore.	$H_8(Mg,Fe)_5Al_2Si_3O_{18}$.					
Serpentine.	$H_4Mg_3Si_2O_9$.	2.5-4.	Fibrous or massive.	Shades of yellow and green.	White.	Smooth, greasy feel. When fibrous forms part of the commercial asbestus. From hydration of magnesian rocks.
Talc.	$H_2Mg_3(SiO_3)_4$.	1-1.2	In smooth scales, sometimes fibrous.	White to pale green.	White.	In massive form is soapstone. From hydration of siliceous magnesian rocks.
Calcite.	$CaCO_3$.	3.	Three equal and perfect cleavages at angles of 75°.	Usually white.	White.	Effervesces readily with HCl. Originates at or near the earth's surface. Largely of organic origin.
Dolomite.	$(Ca,Mg)CO_3$.	3.5-4.	Like calcite, but faces often curved.	White to pearl gray.	White.	Effervesces with HCl in fine powder or when heated. Originates at or near the earth's surface by inorganic action.
Gypsum.	$CaSO_4+2H_2O$.	1.5-2.	One perfect, and two less distinct, giving rhombic plates; sometimes fibrous.	White or light colored.	White.	A chemical precipitate by moderate evaporation. Associated with limestone, marl, or clay.
Iron ores.	.....	.....	.....	.....	.....	Soluble in presence of organic matter. Precipitated and concentrated by oxidation.
Siderite.	$FeCO_3$.	3.5-4.	Like calcite, but faces often curved.	Gray, brownish, or reddish.	White.	Effervesces with HCl in powder or when heated. 40 per cent. heavier than dolomite; 50 per cent. heavier than calcite.
Limonite.	$2Fe_2O_3.3H_2O$.	5-5.5	Not crystallized, but sometimes fibrous.	Brown to yellow.	Yellow.	Yellow ocher. The coloring matter of yellow soils. Occurs earthy, or as stalactites, or as incrustations.
Hematite.	Fe_2O_3.	6.	None.	Red when massive; black when crystalline.	Red.	Red ocher. The coloring matter of red rocks. Results from dehydration of limonite.
Halite.	NaCl.	2.5	Perfect cubic, rather brittle.	Colorless or light colored.	White.	Common salt. Precipitated upon intense evaporation. Occurs with gypsum and marl. Identified by taste and crystalline form.

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	REMARKS.
Quar	treous luster. Irregular fracture. Extremely resistant to decay.
Qu	berated from rocks by the decay of surrounding minerals.
Ce	liceous cement from solution in hot or alkaline waters. In part set free by decay of silicates.
Kaol	ually unctuous and plastic. From decay of aluminous silicates.
Chlo	ually amorphous and forming green stains. From decay of iron and magnesium silicates. Numerous species not easily distinguished.
Cli	
Serp	nooth, greasy feel. When fibrous forms part of the commercial asbestus. From hydration of magnesian rocks.
Talc.	massive form is soapstone. From hydration of siliceous magnesian rocks.
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Dolo	fervesces with HCl in fine powder or when heated. Originates at or near the earth's surface by inorganic action.
Gyps	chemical precipitate by moderate evaporation. Associated with limestone, marl, or clay.
Iron	luble in presence of organic matter. Precipitated and concentrated by oxidation.
Sid	fervesces with HCl in powder or when heated. 40 per cent. heavier than dolomite ; 50 per cent. heavier than calcite.
Lim	llow ocher. The coloring matter of yellow soils. Occurs earthy, or as stalactites, or as incrustations.
He	d ocher. The coloring matter of red rocks. Results from dehydration of limonite.
Halit	mmon salt. Precipitated upon intense evaporation. Occurs with gypsum and marl. Identified by taste and crystalline form.

TABLE III.—SOME MINERALS CHARACTERISTIC OF METAMORPHIC (ANAMORPHIC) ROCKS.

NAME.	CHEMICAL COMPOSITION.	PHYSICAL PROPERTIES.				REMARKS.
		Hardness.	Cleavage.	Color.	Streak.	
Garnet.	$(Ca,Mg,Fe)_3(Al,Fe)_2(SiO_4)_3$.	6.5-7 5	None.	Commonly dark red.	White.	Rounded crystals, often conspicuous. 12 or 24 equal faces.
Tremolite.	$CaMg_3(SiO_3)_4$.	5-6.	Bladed or fibrous.	Wbite to gray.	White.	Wbite bornblende. Wben fibrous, forms asbestus. In marble occurs commonly as sbeaves.
Actinolite.	$Ca(Mg,Fe)_3(SiO_3)_4$.	5-6.	Bladed or fibrous.	Green.	Wbite.	A tremolite with some iron. Ofteu occurs as green matted needles in schists.
Andalusite.	Al_2SiO_5.	7.5	Prismatic; mineral is brittle.	Various ligbt colors.	Wbite.	Isolated prismatic crystals in argillaceous scbists. Broken crystals show a nearly square section and often an internal cross.
Cyanite.	Al_2SiO_5.	5-7.	In flat blades.	Pale blue.	Wbite.	Aggregates of blades. Associated witb quartz. Softened by decay. Developed by intense metamorphism of argillaceous scbists.
Staurolite.	$HFeAl_5Si_2O_{13}$.	7.	Poor ; mineral is brittle.	Sbades of brown.	Pale.	Ratber flat prisms. Crystals often developed as twins, forming an oblique cross. In scbists.
Epidote.	$HCa_2(Al,Fe)_3Si_3O_{13}$.	6-7.	One perfect, and one imperfcct, at angle of 65°.	Commonly yellowisb green.	Grayisb.	Occurs eitber crystallized, granular, or in solid masses. Harder tban serpentinc. Unlike olivine, it is resistant to weatbering.
Tourmaline.	Complex silicate containing aluminum, boron, iron, magnesium, and alkali metals.	7-7.5	Poor ; mineral brittle.	Sometimes brigbt colored, usually black.	White.	Cross sections triangular, somewbat rounded. Associated with quartz in seams and in pegmatite dikes.
Graphite.	C.	1-2.	Flaky.	Black.	Black.	Blackens fingers. Marks paper. From extreme metamorpbism of organic matter.

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Qu ROCKS.

Ce

Kaol

REMARKS.

Chlo ounded crystals, often conspicuous. 12 or 24 equal faces.

'hite hornblende. When fibrous, forms asbestus. In marble occurs
Cli commonly as sheaves.

Serp tremolite with some iron. Often occurs as green matted needles in schists.

Talc. olated prismatic crystals in argillaceous schists. Broken crystals show a nearly square section and often an internal cross.

Calci ggregates of blades. Associated with quartz. Softened by decay. Developed by intense metamorphism of argillaceous schists.

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Iron lackens fingers. Marks paper. From extreme metamorphism of organic matter.

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TABLE IV.—A MEGASCOPIC CLASSIFICATION OF IGNEOUS ROCKS.

CHEMICAL NATURE.	ACIDIC. SiO_2 over 66 Per Cent.	INTERMEDIATE. SiO_2 55 to 66 Per Cent.		BASIC. SiO_2 under 55 Per Cent.
Rock types.	Granite.	Syenite.	Diorite.	Gabbro.
Chief minerals.	Quartz and feldspar.	Feldspar.	Feldspar and hornblende. (Feldspar often striated).	Augite or hornblende.
Typical subordinate minerals.	Mica or hornblende.	Mica or hornblende.	Biotite.	Feldspar, olivine, and magnetite.
Usual color (except in tuffs and glasses).	Light, various.	Light, various.	Gray.	Dark gray to gray-black.

Usual Geological Occurrence.	Texture.	ACIDIC.	INTERMEDIATE.		BASIC.
Beds interstratified with sediments or lava flows.	Fine to coarse fragmental.	Rhyolitic or felsitic tuffs and breccias.	Trachytic or felsitic tuffs and breccias.	Andesitic or felsitic tuffs and breccias.	Basaltic tuffs and breccias.
Lava crusts and some surface flows.	Glassy matrix usually holding some crystals (often vesicular). *Rock glasses.*	Pumice. Obsidian. Pitchstone. Perlite. (All common.)	Pumice. Obsidian. Pitchstone. Perlite. (Not common.)	Pumice. Obsidian. Pitchstone. Perlite. (Not common.)	Scoria. (Common.) Basaltic obsidian or tachylite. (Rare.)
Most extrusions and some thin intrusions.	Matrix of microscopic crystals. *Aphanites.*	Rhyolite or felsite.	Trachyte or felsite.	Andesite or felsite, grading toward and into basalt.	Basalt.
Most intrusions of intermediate volume (dikes, sills, some laccoliths).	Crystals of matrix visible but not distinguishable. *Microphanerites.*	Microgranite. Aplite.	Microsyenite.	Microdiorite.	Diabase.
Massive intrusions (some laccoliths, all batholiths). Abyssal rocks.	All crystals visible and distinguishable. *Phanerites.*	Granite. Pegmatite.	Syenite.	Diorite.	Gabbro. Pyroxenite. Hornblendite. Peridotite.

	BASIC. SiO_2 under 55 Per Cent.
Rock types.	Gabbro.
Chief minerals. nd hornblende. often striated).	Augite or hornblende.
Typical subordi	Feldspar, olivine, and magnetite.
Usual color (exc	Dark gray to gray-black.

Usual Ge	BASIC.
Beds interstrati felsitic tuffs and lava flows.	Basaltic tuffs and breccias.
Lava crusts and	Scoria. (Common.) Basaltic obsidian or tachylite. (Rare.)
on.)	
Most extrusions felsite, grading into basalt.	Basalt.
Most intrusions (dikes, sills,	Diabase.
Massive intrusi batholiths).	Gabbro. Pyroxenite. Hornblendite. Peridotite.

TABLE V.—A CLASSIFICATION OF SEDIMENTARY ROCKS.

CLASSIFICATION.	DISTINGUISHING FEATURES.	MODE OF ORIGIN.
Mecbanical sediments.	.....	Material segregated by pbysical forces.
Visibly granular.	.....	Segregated by creep, sboving, or rolling.
Residual eartbs.	Usually mixed clay, sand, and rock fragments, forming soil wben mixed witb bumus.	No transportation, but formed by removal of soluble portions of rock aud decay of remainder.
Talus breccia.	Angular fragments unstratified. To he distinguished from friction breccias and eruptive breccias.	As talus, from temperature changes, frost, or surf.
Glacial drift.	Subangular fragments, often striated, imbedded in clay.	By transportation upon, within, or under a glacier or ice sbeet.
Conglomerate.	Fragments decidedly rounded hut not necessarily regular.	By transportation of roiling fragments, usually for short distances. The agents are strong river or shore currents.
Sandstone.	Fracture surface rough to tbe finger. Gritty to tbe knife.	By bottom transportation and sorting in shallow water, by moderate river or off-shore currents.
Invisibly granular.	.....	Segregated by floating and settling.
Loess and adobe.	Mostly impalpably fine rock dust. Porous, unstratified.	Formed by wind, by rain-wash, or river-borne silt from glacial or desert regions.
Clay and sbale. Mudstones.	Soft to the knife, even when consolidated. Give earthy odor when damp.	The insoluble portions of minerals suffering rock decay, mostly kaolin, but mixed with some material pulverized witbout decomposition. Deposited in quiet waters.
Novaculite.	Fine-grained and barder tban steel. Suitable for wbetstoues.	Differs from clay and sbale in the high proportion of silica. May often be partly silicified after consolidation by infiltrating solutions.
Cbemical sediments (organic and inorganic).	.....	Material mostly segregated from solution.
Calcareous rocks.	Soft to the knife and effervescing with acid.	In great part from organic remains, but modified by mecbanical action and partial re-solution.
Resulting from organic action.	.....	.....
Sbell limestone.	Containing fossil molluscan shells in abundance.	Accumulated in clear, shallow waters free from mechanical sediments.
Coral limestone.	Containing fragments of coral, but often largely amorpbous.	Accumulated in clear, sballow, and warm seas. Coral largely ground up into a calcareous mud.
Chalk.	Largely made up of (microscopic) foraminiferal shells. Soft, white, and fine-grained.	Accumulated in clear seas from 500 to 14,000 feet in deptb. Mostly from surface-living foraminifera.
Compact limestoue.	Fine-grained. Thin-bedded or massive. Usually gray or bluisb gray.	Made of comminuted or redissolved calcium carbonate, usually originally of organic origin. Fossils subordinate.
Marl and argillaceous limestone.	Often soft and earthy. On solution leaves a large residue. 50 to 70 per cent. calcite.	Originating on lake bottoms, or within 100 to 200 miles of large land masses.
Resulting from inorganic action.	.....	.....
Cement and vein calcite.	Cementing porous materials or filling cavities.	Carried in solution by underground waters and deposited underground.
Tufa and travertine.	Surface incrustations from springs or in caves. Porous or compact, often handed.	Deposited by partial evaporation, or by escape of CO_2 upon meeting tbe air. Sometimes segregated from solutions by algæ.
Oölitic limestone.	Has tbe appearance of a mass of fisb eggs — whence the name.	Formed by a concretionary action on a miuute scale in agitated lime-cbarged waters. Partly of organic origin.
Dolomite.	Distinctly barder tban calcite. Effervesces with hot acid. The powder effervesces slowly witb cold hydrochloric acid. All gradations to limestone.	Made by reaction of magnesium salts with deposits of calcium carbonate, eitber by ocean or hy subterranean waters.
Siliceous rocks of chemical origin.	.....	.....
Resulting from organic action.	.....	.....
Diatom eartb.	Resembles chalk but does not effervesce with acid. Sometimes cemented into flint.	The skeletons of microscopic plants (diatoms) accumulating in lakes and on tbe ocean floor.
Siliceous sinter (geyserite).	Porous and spongy, resembling tufa, but not effervescing witb acid.	Deposited by algæ as gelatinous silica in hot springs, especially geysers. Finally becoming solid but porous.
Resulting from inorganic action.	.....	.....
Siliceous sinter.	Resembling tufa, but not effervescing witb acid. In general, less spongy tban sinter of organic origin.	Deposited from siliceous solutions by evaporation or chemical reaction.
Cbert and flint.	Irregular, fine-grained, massive quartz nodules in limestone. Flint is a more even-grained form in cbalk.	Originally largely organic silica, dissolved from rocks by percolating water. Redeposited and concentrated within the same rocks as concretions.
Siliceous fillings.	Siliceous fillings of pores in sandstones, or fillings of cracks or vesicles.	Deposited from dilute underground solutions. An important agent in cementation.
Carbonaceous rocks.	.....	.....
Coal series.	Specific gravity low, 1.2 to 1.7. All are soft to knife. Coberence varies from that of peat to that of anthracite.	Formed by the partial decay of vegetable matter under swamp waters, witb elimination of hydrocarhons.
Petroleum series.	Usually brown or black (when solid); possessing odor of petroleum. Gases, fluids and soft solids.	Produced cbiefly by partial decay of animal matter in rocks. Often collecting in porous sandstones or limestones. Some deposits are from igneous sources.
Iron ores.	Recognized by streak and otber properties as given under minerals.	Iron dissolved by deoxidizing waters and precipitated where in excess or wbere oxidized.
Evaporation products.	.....	.....
Gypsum.	Softness and lack of effervescence, as given under minerals.	From evaporation of 37 per cent. or more of present sea waters, or prolonged evaporation of inland waters.
Rock salt.	Softness and taste, as given under minerals.	From evaporation of 93 per ccnt. or more of present sea waters, or prolonged evaporation of inland waters.
Alkali.	Wbite crusts, very soluhle, with bitter or alkaline taste. Seldom occur except at surface.	Evaporation of ground water or of alkali lakes in arid climates. Carried to surface by capillarity.

Mechanic forces.

Visibl rolling.

y removal of soluble portions of rock and decay of remainder.

ges, frost, or surf.

or under a glacier or ice sheet.

TABLE VI.—A CLASSIFICATION OF METAMORPHIC ROCKS.

CLASSIFICATION.	DISTINGUISHING FEATURES.	MODE OF ORIGIN.
Rocks made by dominant dynamic metamorphism.	.....	.....
Gneiss.	Coarsely foliated crystalline rocks. Foliation plane only in part controls fracture.	Resulting from masbing, recrystallization, and sometimes igneous injection under high temperatures and pressures.
Gneisses derived from igneous rocks.	Closely resemble igneous rocks in chemical composition. Feldspar usually dominant.	Made as above. Repeated igneous injection often heightens the gneissoid appearance.
Gneisses derived from sedimentary rocks.	Resemble sedimentary rocks in chemical composition. Quartz and mica dominant.	Made by mashing and recrystallization under great pressure. High temperatures, but little or no igneous injection.
Gneisses of unknown origin.	Chemical composition not decisive. Cannot be traced into unaltered formations.	Usually very ancient rocks, which may be sedimentary gneisses transformed by igneous injection.
Crystalline schists.	Closely foliated crystalline rocks, foliation plane controlling fracture.	Resulting from moderate or intense mashing of soft and fine-grained rocks, or intense mashing of coarse or strong rocks.
Slate.	Crystallization microscopic, luster dull (stony), cleavage surfaces plane.	Made by mashing of argillaceous rocks without condition of high temperature.
Phyllite.	Crystallization microscopic, luster silky. Cleavage usually wavy.	Made by masbing of rocks, usually sedimentary and argillaceous, with higher temperature than in slate.
Mica schist.	Crystallization visible. Nothing but mica visible on foliation surface. Other minerals show on cross fracture. Surface often wavy.	Origin similar to phyllite, but temperature higher. Water vapor may aid in crystallization.
Quartz schist.	Cross fracture shows a dominance of quartz in composition. Foliation plane shows mica.	Made by the mashing of sandstone, quartzite, or highly siliceous shales.
Hornblende schist. Amphibolite.	Largely composed of hornblende. When fine-grained, the foliation surface looks like felt. Black to green in color.	Made chiefly from the mashing of basic igneous rocks under high temperatures. Sedimentary rocks also give rise to some hornblende schists.
Various minor schists.	Graphite schist, hematite schist, etc. Distinguished by dominant mineral.	Masbing and crystallization of special rocks, or metamorphism by special processes.
Marble.	Effervesces with acid. Not foliated when pure; when impure, banded and variegated.	Made by mashing and crystallization of carbonate rocks under high or moderately high temperatures.
Rocks made by dominant thermal metamorphism.	.....	.....
Silica rocks.	.....	.....
Quartzite.	Hard, non-porous rocks, fracturing across the quartz grains. Fracture surface smoother than that of sandstone. Appearance vitreous to sugary.	Recrystallization of sandstones, with enlargement of original grains and loss of pore space. Temperature moderate or high.
Silica-alumina rocks.	.....	.....
Hornfels.	Dark rocks, usually with smooth, dull fracture, sometimes with fine granular fracture, often spotted.	Recrystallization of argillaceous rocks under high temperatures, but without mashing or infiltration.
Lime-magnesia rocks.	.....	.....
Marble.	Effervesces with acid. Not banded when pure. A great variety of contact minerals when impure.	Recrystallization of calcareous rocks under high temperatures, but without mashing or infiltration.
Iron ores.	.....	Ores showing recrystallization without attendant mashing. Increase in temperature may crystallize an older deposit, or by favoring infiltration may give rise to a contact deposit of iron ore.
Hematite and magnetite.	Distinguished by their respective mineralogical characters.	....
Mixed types.	.....	May result from recrystallization of mixed types, or from infiltration in a contact zone.
Named according to dominant minerals.	Usually characterized by the notable presence of some uncommon mineral.	.....
Rocks made by dominant hydrothermal metamorphism.	.....	....
Anhydrous rocks.	.....	.....
Quartzite.	May be all gradations from quartzites with sugary fracture, to vitreous quartz rock.	Resulting from recrystallization in the presence of hot water, often with the infiltration of silica, with sometimes the removal of other substances.
Jasper.	Impure opaque colored quartz. Red, yellow, green, or blue. Microscopic grain, chert-like appearance, but in more or less thick formations. Hardness of chert.	More than one mode of origin, but typically due to infiltration of hot waters, resulting in replacement and cementation of fine-grained rocks.
Hydrous rocks.	.....	....
Chlorite schist.	Soft, light to dark green schists, often better termed phyllites.	Where too uniform and deep-seated to be result of surface weathering, the permeation of warm deep-seated waters is indicated. From either sedimentary or igneous rocks.
Talc schist.	Very soft gray to light green schists or phyllites. Sometimes massive. (Soapstones.)	Origin much the same as that of chlorite schist. More siliceous schists with less water.
Serpentine.	Yellowish green to greenish black massive rocks.	From highly magnesian sedimentary or igneous rocks acted upon by deep-seated warm waters.

MODE OF ORIGIN.

Rocks ma.....

Gneis stallization, and sometimes igneous injection under high tem-

Geous injection often heightens the gneissoid appearance.

Gllization under great pressure. High tempera.....

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