FROM·THE·LIBRARY·OF
·WILLIAM·A HILLEBRAND

SIGILLVM·VNIVERSITATIS·CALIFORNIENSIS
FIAT LVX
MDCCCLXVIII

EX LIBRIS

ENGINEERING LIBRARY

ROCKS
AND
ROCK MINERALS

A MANUAL OF THE ELEMENTS OF PETROLOGY WITHOUT THE USE OF THE MICROSCOPE

FOR THE GEOLOGIST, ENGINEER, MINER, ARCHITECT,
ETC., AND FOR INSTRUCTION IN COLLEGES
AND SCHOOLS

W F Hillebrand

BY

LOUIS V. PIRSSON

LATE PROFESSOR OF PHYSICAL GEOLOGY IN THE SHEFFIELD
SCIENTIFIC SCHOOL OF YALE UNIVERSITY

UNIV. OF
CALIFORNIA

TOTAL ISSUE TWELVE THOUSAND

NEW YORK
JOHN WILEY & SONS, Inc.
London: CHAPMAN & HALL, Limited

QE431
P68
Engineering
Library

Hillebrand

Copyright, 1908,
by
LOUIS V. PIRSSON

Entered at Stationers' Ha

ENGINEERING LIBRARY

Stanhope Press
F. H. GILSON COMPANY
BOSTON, U.S.A.

1–25

PREFACE.

During the last fifteen years it has been one of the writer's duties to teach the elements of Petrology to students in various branches of Engineering, Mining, Chemistry, Forestry, etc. The amount of time which these students, in their undergraduate course, can devote to the subject is limited and precludes any attempt to give them such instruction in optical-microscopical methods of research as would be worth while. The subject has to be treated from the purely megascopic standpoint, as indeed the vast majority of those who have to deal with rocks in a practical or technical way are also obliged to consider them.

In giving this instruction the author has long felt the need of a small, concise and practical treatise in which the rocks and rock-minerals are handled entirely from this megascopic standpoint. In such works as exist either the subject matter has not been brought down to date to express our present knowledge of rocks, or it is treated largely from the microscopical or chemical standpoint, or the classifications used are based on microscopical research and are thus not available for ordinary use, or the rocks are treated incidentally with respect to some other main purpose as in works on soils, ore deposits, etc. The present work is an attempt to fill this need which the writer believes is also felt in many other institutions in which similar courses in Petrology are given. In addition to this purpose its scope has also been somewhat enlarged to meet the wants of many who have to consider rocks from the scientific or practical point of view and who are not in a position to use the microscopical method. It is hoped that it may thus prove of service to field geologists,

995702

engineers, chemists, architects, miners, etc., as a handy work of reference. Much of the theoretical side of Petrology which has been developed during the last few years, especially in the line of petrogenesis, does not demand a knowledge of microscopical petrography for its understanding, and the endeavor has been made to present the elements of this in a simple manner. Although the author has incorporated considerable original material it goes without saying that a work of this character must of necessity be mainly one of compilation. It would be nearly impossible and in any case out of place in an elementary treatise to give by reference the thousand and one sources from which the material has been taken. It should be mentioned, however, that in the description of the minerals the writer has drawn freely upon the mineralogies of Dana, Iddings and Rosenbusch and the determinative mineralogy of Brush-Penfield. In the same way in the treatment of the rocks the petrographies of Rosenbusch and Zirkel and the geological text-book of Geikie have been freely used.

Most of the illustrations have been prepared for this work, but the wealth of material in the published reports, bulletins, etc., of the United States Geological Survey has also been freely used.

SHEFFIELD SCIENTIFIC SCHOOL OF YALE UNIVERSITY.
New Haven, Conn., Jan., 1908.

TABLE OF CONTENTS.

PART I.

Introductory and General Considerations.

Chapter | Page
I. SCOPE OF PETROLOGY; HISTORICAL; METHODS OF STUDY 1
II. CHEMICAL CHARACTER OF THE EARTH'S CRUST AND ITS COMPONENT MINERALS 14

PART II.

Rock Minerals.

III. IMPORTANT PROPERTIES OF MINERALS 21
IV. DESCRIPTION OF THE ROCK-MAKING MINERALS . . . 33
V. DETERMINATION OF THE ROCK-MAKING MINERALS . . 114

PART III.

The Rocks.

VI. GENERAL PETROLOGY OF IGNEOUS ROCKS. 132
VII. DESCRIPTION OF IGNEOUS ROCKS 205
VIII. ORIGIN AND CLASSIFICATION OF STRATIFIED ROCKS . 275
IX. DESCRIPTION OF STRATIFIED ROCKS 293
X. ORIGIN, GENERAL CHARACTERS AND CLASSIFICATION OF THE METAMORPHIC ROCKS 333
XI. DESCRIPTION OF METAMORPHIC ROCKS 351
XII. THE DETERMINATION OF ROCKS 398
INDEX 409

ROCKS AND ROCK MINERALS

PART I.

INTRODUCTORY AND GENERAL.

CHAPTER I.

SCOPE OF PETROLOGY; HISTORICAL; METHODS OF STUDY.

EVERYWHERE beneath the mantle of soil and vegetation that covers the surface of the land lies rock, the solid platform upon which the superficial débris of earth rests. Here and there in mountain tops, in cliffs and ledges, we see this underlying rock projecting from the soil and exposed: we know that it must underlie the sea in the same way. The outer shell of the earth then is made of rock, which forms the foundation upon which rest all the surface things with which we are acquainted. How thick this zone of rock is we do not know, but upon it we live and exert our activities; into it we penetrate for coal, oil, gas, metals and other things upon which the material features of our modern civilization depend. It is therefore of the highest importance to us, and the information which we have acquired concerning it, by examination and study, forms a valuable branch of human knowledge.

Petrology — the Science of Rocks. Our knowledge of all the various things which together make up that part of the earth which it is permitted us to examine and study and which has been comprehended under the heading of *Geology* has now increased to such a degree that this science has split up into a number of well-defined, subordinate branches or geological sciences. Thus *Meteorology* is the science of the atmosphere, the summation of our knowledge of the causes and movements of winds, storms, rain, the distribution of heat and cold, and in general the study of the various factors that affect the air and its movements and of the laws that govern them. *Physiography* takes account of the surface features of the earth, of the distribution of land and water and of the agencies which are modifying them, the effects of climates and the various causes which together produce the topography which the earth's surface now exhibits. *Paleontology* is the science resulting from the study of the remains of past life upon the earth, as shown by the fossils inclosed in the rocks, and teaches not only the different forms which have existed but also seeks to discover the transformation of one form into another and the various movements or migrations of life upon the earth in past ages.

Petrology, in the same way, has now become a separate branch, one of the geologic sciences. It comprises our knowledge of the rocks forming the crust of the earth, the results of our studies of the various component materials which form them, of the different factors and the laws governing them which have led to their formation, and of their behavior under the action of the agencies to which they have been subjected, and endeavors to classify the kinds into orderly arrangement.

The terms Petrology and Petrography are not absolute synonyms though often so used in a general way. The former has been defined above; the latter more particularly refers to the description of rocks and especially with respect to their study by means of the microscope as explained later — thus *microscopical petrography.* Petrology is used for the science in its broader aspects as well and covers the geological and chemical relations of rocks: thus strictly defined petrography may be said to be a branch of petrology. The synonym *Lithology* has become nearly obsolete. Petrology means the science of *rocks;* lithology, the science of *stones,* and the word *stone* is now used in a popular way for architectural and commercial purposes or to designate any loose piece of rock of unknown origin.

Definition of a Rock. By the term "rock," geologically speaking, is meant the material composing one of the individual parts of the earth's solid crust, which, if not exposed, everywhere underlies the superficial covering of soil, vegetation or water which lies upon it. The popular understanding of this term, that it denotes a hard or firm substance, is not, geologically, a necessary one, for a soft bed of clay or of volcanic ash is as truly a rock as a mass of the hardest granite. Moreover it implies within limits, which will be explained elsewhere, a certain constancy of chemical and mineral composition of the mass recognized as forming a particular kind of rock. Thus the chance filling of a mineral vein by variable amounts of quartz, calcite and ores is not accepted by petrographers as forming a definite kind of rock. The term is also used with different meanings; it may be denotive of the *substance* forming parts of the earth's crust, as quartz and feldspar arranged in a particular manner are said to form a rock — granite — or it may refer to the masses themselves and thus possess a larger, geological significance. In a general way the former may be said to be a *petrographic*, the latter a *geologic* usage. When used in this broader geologic sense the mass recognized as an individual kind of rock must possess definite boundaries and show by its relations to other rock masses that it owes its existence to a definite geological process. The absolute size of the mass is not involved in this, for a seam or dike of granite cutting rocks of other kinds may be as thin as cardboard or a mile in thickness.

Composition of Rocks. Rocks are sometimes defined as aggregates of one or more minerals, but this is not a broad enough or wholly correct definition. Rocks may be composed entirely of minerals or entirely of glass or of a mixture of both. Minerals are substances having definite chemical compositions and usually of crystalline structure; glasses are molten masses chilled and solidified without definite composition and structure. Rocks composed wholly of minerals may be *simple* or *compound*, that is, the rock may be formed of one kind of mineral alone, as for example, some of the purest marbles which consist of calcite only or of a mixture of two or more like ordinary granite which is made of grains of quartz, feldspar and mica. These subjects are treated more fully in later chapters.

History of Petrology. The science of geology may be said to have commenced when rocks as objects of investigation began to be studied. As the individual minerals composing rocks, or contained in their cavities, were investigated by chemical means and by the goniometer, the science of Mineralogy and its related subject, Crystallography, began. At first the difference between rocks and minerals was not very clearly perceived; very dense rocks composed of mineral grains so fine that they could not be distinguished by the eye or magnifying lens were thought to be homogeneous substances, and similar in their nature to minerals. This continued in many cases even down to the middle of the last century.

As the knowledge of the composition and properties of minerals grew it was seen in the case of the coarser grained rocks that they were composed of aggregates of these mineral grains, and according to the kinds of the component minerals many common rocks had already received names early in the last century. As investigation proceeded and geological science grew many new combinations were discovered and the list of named rocks increased, and it may be remarked here that these early geologists, armed only with a simple lens, were exceedingly keen observers and made many surprisingly correct observations on the mineral composition of quite fine grained rocks. Various schemes of classification were proposed, some of them containing admirable features, but the dense varieties defied the means of investigation then at command, and in great part their composition, properties and relations to other rocks remained unknown.

About the middle of the last century Sorby, an English geologist, showed that, by a suitable method of operation, very thin slices of rocks could be prepared, and by the study of such thin sections under the microscope the kinds of component mineral grains could be made out, their properties and relations to one another, the order in which they had been formed, the processes to which they had been subjected, and many other interesting and important features discovered, and that it was possible to do this even in the case of the densest and most compact rocks. This method of investigation was immediately taken up, especially in Germany by Zirkel and others, and with its advent a new era in the study of rocks and the science of Petrography may be said to have begun. A flood of knowledge regarding rocks and especially of the minerals composing them began to rise and has kept on increasing to the present day. The study of the properties of transparent minerals under the action of polarized light received a great impulse, and the facts discovered have in turn been of immeasurable service in the investigation of rocks by this method. Thus at first attention was directed chiefly to the mineralogical side of petrology; the kinds of minerals of which rocks are composed and their properties were considered of first importance, and this is reflected in the schemes of classification devised at this period. Later, the chemical composition of rocks, both in mass and as shown in their component minerals, their origin and the relations of the different varieties to each other began to attract more attention and have been regarded as of increasing importance down to the present day. This increasing importance of these aspects of the subject is also seen in the weight placed upon them in the more recent schemes of classification proposed for the igneous rocks, those formed by the solidification of the molten masses coming from the earth's interior.

Classification of Rocks. According to their mode of origin and the position of the masses with respect to the earth's crust and to each other, rocks naturally divide themselves into three main groups, divisions which are recognized by practically all geologists. These are the *igneous* rocks made by the solidification of molten material; the *sedimentary* or bedded rocks formed by the precipitation of sediments in water, to which may be added the small group of æolian or wind formed deposits, and the *metamorphic* rocks, those produced by the secondary action of certain processes upon either igneous or sedimentary ones by which their original characters are wholly or partly obscured and replaced by new ones and which are therefore most conveniently considered in a separate group. This grouping will be used in this work, and each group with its further subdivisions, their characters, relations, etc., will be treated by itself.

Summarizing then what has just been stated, we have:

I. Igneous Rocks, solidified molten masses.
II. Sedimentary Rocks, precipitated sediments.
III. Metamorphic Rocks, secondary — formed from I and II.

Field and Petrographic Classifications. The sedimentary rocks are classified in two ways, — in one they are subdivided according to the kinds and fineness of the mineral particles which compose them, in the other according to the geological age, as shown by their position and fossils, in which the sediments were laid down. The first is the petrographic, the second the geological, or more strictly the historical classification, and in this work these rocks are treated only according to the former method. In classifying them they have, so far, been simply divided according to the properties mentioned above, and as they have not yet been the subject of the detailed research which their importance demands, the simple classification adopted by geologists in the field has been followed by the petrographers.

With respect to the igneous rocks and to a lesser degree the metamorphic ones the case is different. The use of the microscope in the study of thin sections has shown that rocks which may appear absolutely identical, either in the field or as one simply compares hand-specimens, may be composed of entirely different minerals, or their chemical analysis may prove them to be fundamentally different in chemical composition. They may thus be quite different rocks deserving separate names and places in any classification in which all of the essential characters of rocks are considered, and yet outwardly to the eye there may be no hint of this. There have arisen two useful terms, *megascopic* (from the Greek μεγας — great) and *microscopic*, the first descriptive of those characters of rocks which can be perceived by the eye alone or aided by a simple pocket-lens, and the second referring to those which require the use of the microscope on thin sections. It is obvious that a classification which is based upon microscopic characters as much as upon megascopic ones cannot be used in determining rocks in the field. It may be more correct and scientific, but in the nature of things it cannot be of general application and use. This subject will be treated of more fully in the section devoted to the igneous rocks, and it is sufficient to say here that the object of this work is to supply a field classification based upon the megascopic characters of rocks to be determined by the eye or pocket-lens, aided by a few simple means for the determination of minerals. In addition many important facts regarding rocks and especially igneous ones have been discovered in these later years which are not dependent upon their classification or microscopic study, and it is intended to give some account of these in a simple general way.

Microscopical Petrography. Although this volume is not based upon the microscopical method of research it will be of interest to indicate briefly how this is conducted and the sort of results obtained by it. To prepare the thin sections or slices of rock for study, a chip of the material as thin as can be obtained is taken. It should be for ordinary purposes about an inch in diameter and of firm unaltered material. It is first ground flat on a metal plate with coarse emery powder and water and then very smooth on another plate with very fine powder. It is then cemented by the aid of heat to a piece of glass with Canada balsam and the other side ground down with the coarse emery until it is as thin as cardboard, or as far as it is possible to carry the operation safely with the coarse powder. It is then in a similar way ground down with the finer powder and finally finished on a glass plate with the finest flour of emery until, in the case of dark, dense rocks, it becomes so thin that ordinary print may be read through it. It is then transferred, after melting the cementing balsam, to a microscopic object glass slide, enveloped in balsam, a thin cover glass placed over it, and it is then ready for use. The professionals who make a business of preparing such sections save much time in the coarser work by the use of sawing disks with diamond dust embedded in them or by using carborundum powder on disks or endless revolving wires. They become very expert in the final grinding and prepare sections whose thickness is quite uniformly about $\frac{1}{1000}$ of an inch, experience having shown that this is best for general work. The appearance of one of these finished sections is shown in Figure 1. By this process the minute mineral grains composing the densest and blackest of basaltic lavas become transparent and may be determined under the microscope.

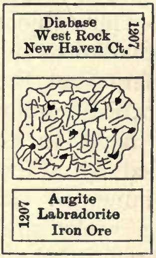
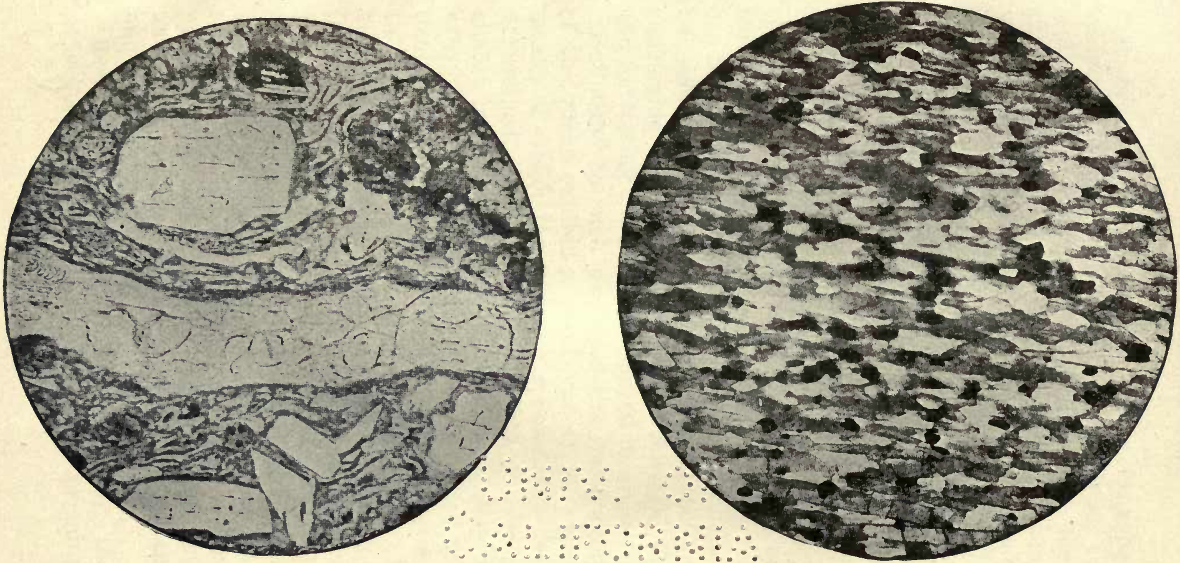


Fig. 1. Thin rock section

The microscope used in petrographic work differs from

PLATE 1.



A. Lava.

B. Schist.

THIN SECTIONS OF ROCKS AS SEEN UNDER THE MICROSCOPE.

(U. S. Geological Survey.)

UNIV. OF CALIFORNIA

that ordinarily employed in being furnished with a variety of apparatus arranged for studying the mineral sections in polarized light. Underneath the table or stage which carries the section is a nicol prism of calcite which polarizes the light coming upward from the reflecting mirror below before it passes through the section, that is, the vibrations of the ether which produce the phenomenon of light instead of occurring in all directions, as in common light, are reduced to a definite direction in one plane.

Another nicol prism called the analyzer is fitted in the tube above the object lens so that the effects produced by the mineral particles on the polarized light, as it passes through them, can be tested and studied. The nicols can be also removed so that the effects of ordinary light can be seen. Other arrangements are provided for strongly converging the light as it passes through the minerals and for testing the results produced in a variety of ways.

Subjected to such processes the transparent minerals of the rocks exhibit a great variety of phenomena by means of which the different species may be definitely determined. Crystals or fragments of crystals of an almost incredible degree of minuteness may be studied with high powers, their properties examined and the particular variety of mineral to which they belong made out. In order to use this means of studying rocks a good knowledge of general Mineralogy, of Crystallography, of Optics, and in particular of the optical properties of the rock-making minerals is essential. Owing to the cost of the apparatus, the technical knowledge required in its use and the difficulty of making thin sections, it is obvious that this method of studying rocks can never become a popular or general one, but many of the results which have been attained by it are easily understandable and may be mentioned.

Results of Microscopic Research. By the method described above the kind of mineral or mineral grains making up the most compact and dense rocks may be determined; whether the rock is of sedimentary or igneous origin can be told and, if the latter, the general order in which the mineral varieties have crystallized from the molten fluid. It can be seen whether the crystal particles are clear and homogeneous or if they contain inclusions of various kinds, facts which often throw light on their origin and history; whether they are fresh and unchanged or have been decayed by the action of the elements and altered wholly or partly into other substances; whether they have been subjected to the enormous pressures of mountain building in the crust and are strained and crushed or not. It is possible to tell at once if a rock contains more or less glass associated with the mineral grains, and if it does, to thus learn with certainty its igneous origin and the fact that in all probability it is a surface lava, — glass, in the nature of things, being almost entirely confined to such rocks.

Furthermore, if the grains are not too microscopically fine it may be possible, not only to determine the kinds of minerals they are, but to measure their areas or diameters in a given section, ascertain from this the relative proportions of the different kinds of grains present, and then, when the chemical composition of the component minerals is known, compute the chemical composition of the rock mass as a whole, a factor, especially in the case of igneous rocks, often of great importance in scientific classification and in other ways.

These are some of the more important features of rocks which may be discovered by their microscopic study, and they are sufficient to illustrate the value of the method in aiding geological research.*

---

* The following works in which rock-making minerals and rocks are treated and classified according to the results of microscopical research in a more or less extensive and detailed way may be mentioned: Rock Minerals, by J. P. Iddings (Wiley and Sons, New York). Quantitative Classification of Igneous Rocks, by Messrs. Cross, Iddings,

Megascopic Study of Rocks. Although the microscope is necessary for the complete investigation of rocks many of their important features may be observed without its use. In the case of the coarser grained ones, those where the size of the grains is one-sixteenth of an inch in diameter or more, the component minerals can usually be identified by the aid of the lens or by simple means. Even when much finer grained than this, some minerals may be distinguished by certain characters they possess as explained in the chapter on the rock-making minerals. Even when they are so dense that the component grains can no longer be discriminated from each other, the color, the hardness, the style of fracture under the hammer, the specific gravity and the behavior of fragments or of the powdered rock under the action of acids, are all important characters which serve to distinguish different kinds of rocks.

Implements and Apparatus. The first requisite is a suitable hammer for obtaining material. It should be a square-faced geological hammer of the type shown in the adjoining figure. It is convenient to have one end wedge shaped. The steel should be tempered as hard as possible without making it too brittle, otherwise the edges wear off very rapidly. If made to order it is a great convenience to have the hole as large as possible, consistent with strength, and tapered somewhat; the handle may then be somewhat larger at the hammer end and thrust through the hole until brought up in the taper by the enlarged end. This device, which is the familiar one used in securing the handles of picks, is a great convenience as it prevents the head coming off when the

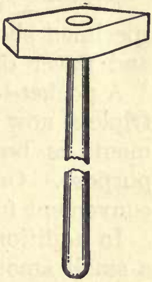


Fig. 2. Geological hammer

Pirsson and Washington (Chicago University Press). Elemente der Gesteinslehre, by H. Rosenbusch (Stuttgart). Petrology for Students, by A. Harker (Cambridge University Press). Igneous Rocks, by J. P. Iddings (Wiley & Sons, New York).

handle shrinks. The hammer should be of good weight, about two and one-half pounds for the head, to enable good-sized pieces of rock to be readily broken up and fresh material within to be secured. Of course anything in the way of a hammer or sledge may be used on occasion, but this implement will give the best service for general use.

If, in addition to procuring material for examination, it is desired to trim and shape it into specimens for the collection a small trimming hammer will be found convenient. It should be double-headed, square-faced, and of very hard steel, and the head may weigh about six ounces. Hand specimens for collections are usually about 4 × 3 × 1 inches in size and are made by selecting a suitable large flake or spall obtained by the large hammer and knocking small chips from it along the edges first on one side and then on the other until trimmed to the required shape and size. A well-made specimen should show hammer marks only on the edges and never on the faces.

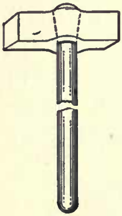


Fig. 3. Trimming hammer

A pocket-lens is also essential; one of the apochromatic triplets now made by several makers of optical instruments is best, but much cheaper ones will serve the purpose. One with a focal distance of one inch is most convenient for general use.

In addition to the above, which are for use in the field, a small amount of the apparatus used in the laboratory for the determination of minerals will often prove of great service. This would include a blowpipe and platinum tipped forceps for testing fusibility, pieces of quartz, calcite and ordinary window glass for testing hardness, a simple apparatus for determining specific gravity, a magnet, a few test tubes, dilute acids and a Bunsen gas burner or alcohol lamp for testing solubility, and a glass funnel, filter paper and a few reagents, such as solutions of ammonia, silver nitrate and barium chloride, for making tests by chemical reactions. A small agate or steel mortar is needed for grinding a fragment of the rock or mineral to powder for making chemical tests. This list might be increased almost indefinitely into the full equipment of a mineralogical laboratory, but most chemical laboratories contain all the apparatus and reagents necessary for the determination of minerals and rocks mentioned in this book and, where such a laboratory is not available, the material which has been named above will cover nearly all necessary demands and may be used almost anywhere.

CHAPTER II.

CHEMICAL CHARACTER OF THE EARTH'S CRUST AND ITS COMPONENT MINERALS.

Composition of the Earth's Interior. The origin and history of the rocks composing the solid crust of the earth are of necessity bound up with the history and origin of the globe itself. Beyond that history, however, which is revealed in the sedimentary rocks, our ideas on this subject, as regards the earth, must, with our present knowledge, be largely of the nature of pure speculation. Below a relatively very shallow depth the same is true with respect to the character and condition of its interior. We do not know what it is like, and it is of course possible that we never shall. The view which is most generally held is that the earth was once a molten mass, the outer shell of which solidified through cooling to a solid crust, while the interior, though excessively hot, also solidified through the enormous pressures exerted upon it by the overlying portions; between the two is either a zone of liquid because the pressure is not there sufficient to solidify it, or of heated material which will become liquid if for any cause the pressure in the crust above is diminished; this zone is regarded as the seat of volcanic and other important geological activities.

While this view has been long and is still widely held and has been of great service in explaining many geological phenomena, certain objections to it have been advanced, and recently Chamberlain has propounded another.

According to this the earth is regarded as never having been liquid but always a solid which has been gradually built up by the infall and accretion of relatively small solid bodies termed planetesimals. Through the enormous pressures exerted under the influence of gravity, contraction has ensued and gaseous matters have been expelled, giving rise to the atmosphere and water on the surface. This contraction is held to be the source of the interior heat, and to the issuance of the heated gases is attributed the origin of volcanic activity.

Still another view has been advanced in recent years by Arrhenius according to which the interior is neither in a solid or liquid but in a gaseous condition. It is assumed that all substances if sufficiently heated must be in the state of a gas; experiment teaches us that if any gas is heated to or above a certain degree called its " critical temperature " it cannot be reduced to a liquid or solid by pressure alone, and it is held that this will be true even though the pressure be enormous enough to contract the gases to a density far beyond that which the substances would have if in the solid condition. It is assumed that the temperatures reigning in the earth's interior are so great that all substances must be in a gaseous condition and above their critical temperatures, but that the pressures are also so enormous that they are reduced to a state of density far greater than that of solids at the surface, and that on account of this condensation their internal viscosity or resistance to flowage is so great that they possess also a greater rigidity, one sufficient to meet the demand which astronomical investigations have shown that the earth as a whole must possess.

Following this view then there is, first, a solid outer crust, then a zone of molten liquid or of solid material so greatly heated that it is capable of becoming liquid if the pressure above is in any way lightened, and then finally the great interior mass consisting of heated gases in a condition of enormous condensation.

The three hypotheses presented above will serve to show how widely divergent are the views in regard to this subject among scientific men at the present time and how purely speculative our ideas must be.

Facts which are known. On the other hand it must not be assumed that nothing is known of the earth beyond that which we can see at the surface. We know, for instance, that there is a considerable increase in heat as we go downward in the crust. We know also that there are bodies of molten material, which, though they may be relatively small as compared with the size of the earth, are yet absolutely large, and we see the upward prolongation to the surface of these masses in active volcanoes. We know that such bodies not only exist in the earth's interior now but have also in past geological ages, as shown by the way in which they have been forced upward into its crust or poured out upon its surface. We know that upon the land surfaces wherever the deepest seated rocks, which underlie all the stratified and metamorphic ones which have accumulated upon them, are exposed by erosion they present the general characters of igneous rocks, and thus lead us to infer that they were at one time in a state of fusion. As the sedimentary and metamorphic rocks are secondary or derived from previously existent ones, this leads to the natural assumption that they came from material originally similar to these deep-seated ones and that their substance had at some previous stage passed through a state of fusion.

Rock material then having been wholly or at least very largely in a molten condition, it is evidently a matter of importance that we should know something of the nature and properties of the molten fluids which have formed it. We can do this to some extent in active volcanoes where we see some of the properties of these fluids exhibited, but those which are most important in rock formation we can best learn by study of the igneous rocks which are the result of the direct solidification of these molten masses, and this subject is, therefore, treated in the chapter upon them. There are, however, certain aspects of it which can well be considered here, and one of these is the general chemical composition of the earth's crust.

Chemical Composition of the Earth's Crust. During recent years several thousand chemical analyses have been made of rock specimens from visible parts of the earth's crust. The great majority of them are from Europe and the United States, but enough have been made from other parts of the world to show, in conjunction with the microscopical studies of other specimens, that the essential facts which these analyses teach are almost beyond question of general application. One of the most important general truths learned by these investigations may be thus broadly stated — the general chemical composition of the earth's crust is everywhere similar.

The statement thus broadly made demands explanation. It does not mean that one portion of the rock crust is composed of exactly the same chemical elements in exactly the same proportions as any other portion. It means that it is composed of the same elements and that, although these may vary greatly in proportions from place to place or from one kind of rock mass to another, if we take large areas involving many kinds of rocks the average of such areas will be very nearly alike. Thus the composition of the average rock computed from all the analyses made of specimens from the United States is essentially the same as the average computed from the analyses of the rocks of Europe. The average rock of New England is essentially that of the Rocky Mountains region. On the other hand a large part of Quebec Province is composed of one kind of rock which extends with monotonous sameness over a vast area; the composition of this has not the same proportions as the average rock, and if we were considering this particular part of the continent we should have to increase greatly our area to obtain an average. Some parts of the continental areas are covered with limestone which is essentially carbonate of lime alone, but is a relatively thin, concentrated coating of a special substance — we should have to balance it with large masses of other rocks.

The average rock has been computed from the analyses by Clarke and by Washington and the results are shown in the table below in Column A.

	A 93 Per Cent Lithosphere.	B 7 Per Cent The Ocean.	C Average with Atmosphere.
Oxygen	47.07	85.79	49.77
Silicon	28.06	...	26.08
Aluminum	7.90	...	7.34
Iron	4.43	...	4.11
Calcium	3.44	0.05	3.19
Magnesium	2.40	0.14	2.24
Sodium	2.43	1.14	2.33
Potassium	2.45	0.04	2.28
Hydrogen	0.22	10.67	0.95
Titanium	0.40	...	0.39
Carbon	0.20	0.002	0.18
Chlorine	0.07	2.07	0.21
Phosphorus	0.11	...	0.10
Sulphur	0.11	0.09	0.10
All others	0.71	0.008	0.73
	100.00	100.000	100.00

Clarke has also calculated that if we assume that the crust has this composition to a depth of ten miles and add in the water of the oceans, the atmosphere and an amount of sedimentary rocks in proper proportions, the general average of the whole will be that shown in Column C, of the above table. These assumptions are reasonable, and correspond with the facts so far as known. Even if these results are not very accurate they must be approximately so and they are of value in showing the relative proportions of the elements in the outer part of the earth. From them important deductions can be drawn.

The Elements of Geological Importance. From the table just given we see that the first eight elements are present in quantity, and are, therefore, of geologic importance. Oxygen forms about one half of the outer part of the earth, and the quantity in the atmosphere and in the ocean is small, compared with that locked up in the underlying rock. Silicon comes next and forms about one fourth and after it are aluminium and five other metals, of which iron is the most important, the others being calcium, magnesium, sodium and potassium, in the order of their importance. After these comes a small group of four elements, which, although of secondary rank in quantity, demand mention: they are, hydrogen, titanium, carbon and chlorine. Of these, titanium is a rather inert element from the geological standpoint, plays no important part in geological processes or results, and may, therefore, be dismissed. The hydrogen and carbon, on the contrary, are of great importance, they are of great activity in geological processes, produce results of petrologic interest, and must therefore be considered with the primary group first mentioned. All the other elements, however important in special cases, or for organic life or civilized activities, are from the standpoint of general geology and petrology of relatively little interest.

Combinations of Chemical Elements. Except oxygen, carbon, and possibly to an unimportant extent iron, the elements mentioned above do not occur alone, or native; they are always combined in some form producing compounds known as minerals. We may state this chemically by saying that they are either in combination with oxygen as oxides, or these oxides are in combination as salts. Two, carbon and silicon, are negative elements — their oxides CO_2 and SiO_2 are anhydrides of acids; the others, leaving hydrogen aside, are metals, or positive elements whose oxides act as bases. The oxide of aluminium, Al_2O_3, acts sometimes as a base and sometimes as a weak acid, especially in combination with strong positive bases, such as soda, Na_2O, and potassa, K_2O, and in combination with silica, SiO_2. Fe_2O_3 acts as an acid in spinels.

From what has been said we have to deal with these oxides which are of chief petrologic importance.

ACIDIC OXIDES.

SiO_2, silica, in combination and free as a solid.
CO_2, carbon dioxide, in combination and free as gas.

BASIC OXIDES.

Al_2O_3, alumina, in combination and free solid, sometimes acidic.
Fe_2O_3, ferric oxide, in combination and free solid.
FeO, ferrous oxide — only in combination in solids.
MgO, magnesia, in combination and free, solid.*
CaO, lime — only in combination in solids.
Na_2O, soda — only in combination in solids.
K_2O, potassa — only in combination in solids.

The above table is given in order of decreasing acidity and increasing basicity from top to bottom. To this list we should also add water, H_2O, which occurs free in the gaseous, solid and liquid states, and in combination.

Since we are considering rocks it is evident that of these oxides and their combinations we need to regard only those which form solids. They are then the compounds of silicic and carbonic acid or silicates and carbonates and the oxides of silica, alumina and iron.

Ice, the solid form of water, may also be regarded as a rock, but as such, needs no further consideration in this work. Combinations of the oxides of aluminium, iron and magnesium and of the silicates with water also occur. Combinations with sulphur as sulphides and sulphates and of phosphorus as phosphates and of chlorine as chlorides are at times of local importance though never having the general interest of those mentioned above. They receive attention in their appropriate places.

---

* The solid MgO is the mineral periclase, excessively rare, and of no petrologic importance.

PART II.

ROCK MINERALS.

CHAPTER III.

IMPORTANT PROPERTIES OF MINERALS.

SINCE all rocks, with the exception of a few glassy ones of igneous origin, are composed of minerals it is of first importance in their study and determination that a good knowledge of the important rock-making minerals, of their obvious characters and properties, should be had. This is so indispensable, that before taking up the rocks themselves, the following part of this work is devoted: first, to a general account of those properties of minerals which are of value in megascopic determination; second, in a succeeding chapter, to a description of the minerals individually; and third, to methods for their determination.

Minerals defined. A mineral is defined as any inorganic substance occurring in nature which possesses a definite chemical composition. To this, for petrographic purposes we should add, that it is also a solid and usually it has a definite crystalline structure. The word is also used in two ways with different meanings: in one, which may be termed the abstract chemical way, we refer to a compound having a certain composition, as in speaking of calcite we mean the compound $CaCO_3$, carbonate of lime; in the other when we speak of the minerals of a rock we refer to the actual crystal grains, the minerals as distinct entities or bodies which compose that rock.

Crystals defined. Most chemical compounds when their molecules are free to arrange themselves in space and the conditions are proper for them to assume solid form, as for example when they solidify from solutions, appear in *crystals*. That is, the molecules arrange themselves in a definite geometric system, characteristic of that compound, and governed by mathematical laws, which give the solid a definite internal structure and an outward form bounded by planes which are always placed at certain angles to one another. Thus minerals crystallize in cubes, octahedrons, prisms, etc. The conditions in rock formation are sometimes such that a mineral can assume outward crystal form, and it is then bounded by distinct planes; more commonly, however, the growing crystals interfere with one another and have no distinct form, or, as in the sedimentary rocks, they are fragments only of former crystals, or their plane surfaces have been worn off by attrition. Since, however, they possess the inward characteristic structure we still call such bodies crystals, though lacking the outward form. Thus, when we speak of the crystals or crystal grains composing a rock, we do not necessarily imply that these have plane surfaces which give them geometric forms. Such grains are sometimes called *anhedrons* (from the Greek, meaning, without planes).

List of Properties. The chief properties of the rock-making minerals by which they may be known are their *crystal form, color, cleavage* and *associations;* these are perceived by the eye, and in addition we have their *hardness, specific gravity,* and their behavior *before the blowpipe* and with *chemical reagents,* properties which demand some form of testing with apparatus.

Crystal form. The mineral grains which compose rocks do not, as a rule, possess good outward crystal form as mentioned in a preceding paragraph. The reason for this is that in the igneous and metamorphic rocks, the growing minerals interfere with one another's development, and thus, while they may roughly approximate to a certain general shape the mineral has endeavored to assume, the outer surface is not composed of smooth definite planes; while in the sedimentary rocks the grains are either broken fragments or rounded by rolling and grinding. It may happen, however, that in a liquid molten mass when crystallization begins, one or more kinds of minerals may commence growing in crystals scattered through it and complete their period of growth before the others which will compose the general mass of the rock have commenced. In this case they have not been interfered with, and they may exhibit good outward crystal forms bounded by distinct planes. This is well shown in those kinds of igneous rocks which are described elsewhere as *porphyries.* Likewise in the metamorphic rocks, certain minerals often appear in such well-bounded, distinct crystals, as to indicate that they are of later origin, and although formed by molecular rearrangement of materials in a solid or somewhat plastic mass the conditions were such that they were not interfered with during their period of growth. This is illustrated by the excellent crystals of garnet, often seen in the rock known as *mica schist.*

Thus in general the outward crystal form or shape of minerals in rocks is wanting and cannot be used as a means for determining them, but in many special cases it may be well developed in rock-making minerals and it can then be very useful. The shapes in which each mineral is most apt to occur are described under the heading of that mineral in the descriptive part.

Color. The color of minerals, when used with proper precautions, is also a very useful property for helping to distinguish them. The color of minerals is dependent upon their chemical composition, in which case it may be said to be *inherent,* or it may be due to some foreign substance distributed through them and acting as a pigment, and their color may then be termed *exotic.* It is because the color of the mineral grains of rocks is frequently exotic that precaution must be used in employing it as a means of discrimination.

In regard to *inherent* colors, neither silica nor carbonic acid in combination as silicates and carbonates has any capability for producing color, and so far as they are concerned, such compounds would be colorless, or, as will be presently explained, white. So, silica alone, as quartz, is naturally colorless. The same is also true of the metallic oxides alumina, lime, magnesia, and the alkalies soda and potash. Thus, carbonate of lime or calcite, carbonate of lime and magnesia or dolomite, oxide of alumina or corundum, silicates of lime and magnesia, silicates of alumina and the alkalies or feldspars are all inherently colorless minerals. The metallic oxides which chiefly influence the color of rock minerals are those of iron, chromium and manganese, and the only one of these which is of wide petrographic importance is iron, especially iron as ferric oxide. The minerals containing iron as a prominent component are dark green, dark brown or black, and these colors may ordinarily be regarded as indicative of this metal.

With respect to the *exotic* colors which minerals frequently exhibit, this may be due to one of two causes. It may happen that a minute amount of some compound of an intensely colorative character is present in chemical combination. Thus a minute amount of manganese oxide in quartz is supposed to produce the amethyst color, traces of chromic oxide sometimes color silicates green, and probably copper does also. Or the color may be due to a vast number of minute bodies dispersed through the crystal as inclusions. These minute specks may have a distinct color of their own and thus act as a pigment, as when, for example, quartz is colored dark red by a reddish dust of ferric oxide particles in it; or the inclusions may be so arranged in regular systems as to act refractively upon light, breaking it up and producing a play of prismatic colors, or opalescence in the substance. Usually in the latter case, one color predominates and gives its character to the mineral. A good example of this is seen in the variety of feldspar called labradorite, a constituent of the rocks called *anorthosite* and *gabbro,* which often shows a fine play of colors, a rich dark blue being usually predominant.

The *white color* which so many rock-making minerals exhibit may be due to minute inclusions, as when feldspars are sometimes, through alteration, filled with scales of kaolin or white mica, but more commonly it is due to the reflection of light from the surfaces of innumerable microscopic cracks and crevices which everywhere permeate the mineral substance. In such cases the material is really colorless and transparent. The effect is the same as if a piece of colorless glass should be ground to powder, which would of course be white. Hence white minerals are not regarded as possessing any color, and they are often free from such cracks and are then colorless and transparent. Good examples of this are seen in such common minerals as quartz, calcite and feldspars. As explained under cleavage, these cracks in feldspar are sometimes so regularly arranged as to produce a play of colors, giving the mineral an opalescence or pearly luster with a distinctly predominating color tone like that mentioned above as produced by inclusions.

Streak. In addition to that color which minerals show in the solid form, there is another way in which this property may be often usefully employed in determining them. This is the color which the substance presents when reduced to a state of powder. The powder may be obtained by grinding a small fragment in a mortar, but it is more easily produced by scratching a sharp point of the mineral across a plate of unglazed porcelain; the color of the resultant streak is of course that of the powdered mineral. While any piece of unglazed porcelain will answer fairly well, small plates are specially made for this purpose and sold by dealers in chemical apparatus.

The color shown by minerals in the powdered state is usually much lighter than that which they exhibit in the mass and sometimes very different. It is most useful in helping to discriminate the dark colored minerals, especially the metallic oxides and sulphides of the heavy metals used as ores, and hence its application with the light colored silicates and carbonates that chiefly form the rock-making minerals is much more limited and of lesser value. In the case of these minerals it is sometimes useful in distinguishing exotic from natural colors; for the color of the streak is generally that of the mineral substance itself, and the pigment or other impurities which produce an exotic color must be present in very large amount to exert a definite influence. Thus calcite is colorless or white, but sometimes yellow, brown or red, but the streak of all these colors is white or barely tinted except in unusual instances. The feldspars are normally white or colorless, but in some rocks, such as *anorthosite,* they sometimes are black and at first glance might be mistaken for an iron-bearing mineral; the streak, however, is white and helps to show their true character.

In the field, the bruised surface of the rock, where struck by the hammer, often shows the powdered minerals, giving in a rough manner the color of the streak; or a bit of the substance may be ground between two hammer surfaces and the powder rubbed on white paper.

Cleavage. When mineral bodies possess crystalline structure, it frequently happens that the arrangement of the physical molecules composing them is such, that the force of cohesion among them is less in some particular direction or directions than in others. Along such directions, if suitable means be employed, such as placing the edge of a knife upon the mineral and striking with a hammer, the body will tend to split or cleave. The degree of perfection with which minerals possess this property is very variable; some, like mica, which is used for stove windows and lamp chimneys, are capable of being almost indefinitely split into thin leaves; others, like the feldspars, have a good cleavage; while some, like quartz, have no apparent cleavage. When the cleavage is very good the new surfaces are smooth and shining like the original ones of a crystal and it is termed *perfect.* This property, being then so distinctive, is a most useful one in helping to determine minerals, especially in rocks where the mineral grains on the surface, broken by the hammer, if they possess it, everywhere show shining cleavage faces. It must not be imagined that the directions of cleavage occur at random in a mineral; on the contrary, they always bear a definite relation to the special crystal form that characterizes a particular mineral. If the latter has two directions in which it may be cleaved, like feldspar, for example, the angle between the two surfaces is, for a feldspar of a certain definite chemical composition, always the same. Some minerals, like mica, have only one direction in which there is good cleavage; others have two directions, and sometimes the two are exactly alike and sometimes unlike, one being better than the other; again there may be three directions in which cleavage can be produced, all alike as in calcite or unlike as in barite (heavy spar, $BaSO_4$), or there may even be four or more. Whether the cleavages are alike or unlike, when there is more than one, depends not only on their direction in the crystal, but also on the geometric form or system of crystallization the latter exhibits. A description of these relations would involve too much of the principles of crystallography for discussion in this place, but the following will be helpful in understanding certain terms frequently used.

A. Good cleavage in one direction only: the mineral grains in the rock in this case are apt to be developed in tables, folia, or scales, whose surface is parallel to the cleavage. This is well shown in such minerals as the micas and chlorite.

B. Good cleavage in two directions and both alike: the minerals are apt to be developed in elongated forms parallel to the cleavage, and the latter is spoken of as being *prismatic*. This is shown by the minerals hornblende and pyroxene. If the two cleavages are not exactly alike, the mineral still is often elongated in the direction of the edge produced by the meeting of the two cleavage planes. It may be sometimes columnar and sometimes tabular parallel to the better cleavage. The feldspars, which form the free developed crystals in porphyry, often show such relations.

C. Good cleavage in three directions alike: if the three planes are at right angles to each other the mineral will break up into cubes and the cleavage is *cubic* or apparently so; if they are at some other angle, rhombs will be produced and the cleavage is called *rhombohedral.* Cubic cleavage is well shown by galena, PbS, the common ore of lead and by rock salt; it is not exhibited by any common rock-making mineral. Rhombohedral cleavage is characteristic of the common rock-making carbonates, calcite, $CaCO_3$, and dolomite $(MgCa)CO_3$. Three unlike directions have the same practical effect as two unlike, and four directions are not of importance in megascopic petrography, as no common rock-making mineral exhibits them.

If a rock with component mineral grains sufficiently coarse so that they can be readily studied by the pocket-lens, the size of peas, for example, be carefully examined, it will be found that almost without exception, where a mineral shows a cleavage face, it will be full of minute cracks and fissures. These cracks are parallel sometimes to one cleavage and sometimes to all the cleavage directions the mineral has. In addition to the cleavage cracks there are also irregular lines of fracture which do not correspond to any definite direction. Commonly, the mineral grains of rocks contain not only these large cleavage cracks and irregular fractures which can be perceived with the eye or with the aid of the lens, but, in addition, they are everywhere rifted by similar ones so minute that they can only be detected in thin sections of rocks under high powers of the microscope. It is the reflection of light from these minute microscopic cracks that renders so many minerals opaque and white in color that would otherwise be colorless and transparent. These cracks and fissures have been produced in the rocks by the various forces to which they have been subjected; sometimes they are due to the contraction following a heated stage as in metamorphic and igneous rocks, and sometimes and more generally to the intense pressures and strains to which the rocks of the earth's crust are and have been subjected. Minute as the rifts in the mineral grains are, they are of great importance in geologic processes, for by means of them, and drawn by capillary action with great force, water containing CO_2 in solution penetrates not only the rocks but the individual grains as well, to their very interiors, and alters and changes them into other minerals and the rocks into soil.

Fracture. The appearance of the breakage of minerals in directions which are not those of cleavage or in cases where the mineral does not possess cleavage is called its *fracture.* If the mineral is fibrous in structure, the fracture may be *fibrous;* or it may be rough and uneven or *hackly;* if the mineral is dense, compact and homogeneous it will be *conchoidal,* that is, it will present a sort of shelly appearance such as is shown on surfaces of broken glass which recall the inside or outside of a clam shell. Rocks which are extremely dense and homogeneous, like some flints, or glassy lavas or fine-grained compact ones, have also a conchoidal fracture more or less pronounced. Quartz is the most common mineral which gives a good example of conchoidal fracture.

Fig. 4. Conchoidal fracture in obsidian volcanic glass.

Associations of Minerals. The facts that certain kinds of minerals are apt to be found together in the same kind of rock and that the presence of one mineral excludes the presence of some other mineral are of great value in petrography but of much greater use in microscopic work, where the distinguishing characters of minerals are easily made out, than in field determinations. Even in megascopic petrography, however, these facts are at times of practical use; thus the fact that the two minerals, quartz and nephelite, cannot occur naturally together as rock-making components is of value in discriminating between certain rocks. The various relations of this kind that are of importance will be mentioned in their appropriate places.

Hardness. This property is of great value in helping to make determinations of minerals, and it is likewise very useful in the field in making rough tests of rocks. The hardness of minerals is determined by comparing them with the following scale:

Scale of Hardness

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

This means that each mineral, using a sharp point, will scratch smooth surfaces of all the minerals in the list above it but of none below it. If, for example, a fragment of an unknown mineral is found to scratch calcite its hardness is greater than 3; if it will not scratch fluorite, but, on the contrary, is scratched by it, its hardness is not so great as 4, but must be between 3 and 4 or approximately $3\frac{1}{2}$.

The point of a pocket-knife blade as ordinarily tempered with a hardness of a little over 5 and pieces of common window glass with hardness of about $5\frac{1}{2}$ are very useful for testing the hardness of common minerals and of the rocks made up of them. A common brass pin point is a little over 3 and will scratch calcite; the finger nail is a little over 2 and will scratch gypsum.

Specific Gravity. The specific gravity of a substance is its density compared with water or the number of times heavier a given volume of the substance is than an equal volume of water. It is obtained by weighing a piece of the mineral or rock in air and then in water; the difference between the two is equal to the weight of an equal volume of water (the volume displaced) and we have

$$\frac{\text{wt. in air}}{\text{wt. in air} - \text{wt. in water}} = \text{Sp. Gr.}$$

The operation may be carried out with one of the special forms of apparatus devised for determining specific gravity and described in the manuals of determinative mineralogy, or it may be done with a chemical, an assay or a jeweler's balance. It is first weighed in the pan and then suspended from it by a hair and weighed in water.

SPECIFIC GRAVITIES OF ROCK MINERALS.

ARRANGED IN DESCENDING ORDER.

5.2	Magnetite.	2.86	Muscovite.
5.2	Hematite	2.85	Dolomite.
4.9–5.1	Pyrite.	2.80	Talc.
4.7–5.1	Ilmenite.	2.75	Anorthite.
3.95–4.1	Corundum.	2.73	Labradorite.
3.6–4.0	Limonite.	2.72	Calcite.
3.5–4.2	Garnet.	2.65–2.75	Chlorite.
3.75	Staurolite.	2.66	Quartz.
3.5	Topaz.	2.62	Albite.
3.56–3.66	Cyanite.	2.6	Kaolin.
3.4	Vesuvianite.	2.5–2.65	Serpentine.
3.2–3.5	Pyroxene.	2.57	Orthoclase.
3.27–3.37	Olivine.	2.55–2.65	Nephelite.
3.25–3.45	Epidote.	2.45–2.50	Leucite.
3.0–3.4	Amphibole.	2.32	Gypsum.
3.16–3.2	Andalusite.	2.27	Analcite.
3.1–3.2	Chondrodite.	2.25	Natrolite.
3.15	Apatite.	2.15–2.30	Sodalite.
3.0–3.15	Tourmaline.	2.15–2.2	Heulandite.
2.95	Anhydrite.	2.1–2.2	Stilbite.
2.8–3.1	Biotite.	2.1–2.2	Opal.

A piece about one-half inch in diameter is convenient both for minerals and rocks, but in the case of minerals it is frequently necessary to select a fragment smaller than this to obtain pure homogeneous material, without which it is perhaps needless to say the determination is of little value. Adherent air bubbles and air in cracks are best gotten rid of by boiling the fragment in water and then allowing it to cool before weighing. If the mineral has an invariable chemical composition and crystal form, as for example, quartz (SiO_2), calcite ($CaCO_3$), etc., the specific gravity is an invariable quantity, and departures from it must be due to the presence of impurities. Many minerals, however, while they retain the same crystal form, vary considerably in chemical composition in that one metallic oxide may be more or less replaced by another similar oxide or oxides. Thus we find minerals which at one end of a series contain magnesia, MgO, and at the other end ferrous oxide, FeO, and between these extremes all degrees of mixtures of these two oxides. In accordance with such variations the specific gravity of the mineral varies. The pyroxenes, amphiboles, garnets, olivines, etc., are examples of this, and it accounts for most of the variations in specific gravity which may be observed in the annexed table.

Blowpipe Reactions. The rock-making minerals, which are chiefly carbonates and silicates, do not as a rule exhibit before the blowpipe very characteristic reactions by which they may be readily determined, as do so many of the ores, the oxides and sulphides of the heavy metals. Still, however, the relative degree of *fusibility* shown by thin splinters, the *coloration of the flame* and the characters of the melted *bead* which may result are properties which may be of great service in helping to determine these minerals, and so far as they have value in this direction they are mentioned in the description of the minerals. If instruction in the use of the blowpipe is desired it should be sought in one of the manuals devoted to that purpose.

Chemical Reactions with Reagents. Certain qualitative chemical tests which can generally be made with a few reagents and simple apparatus are of great service in mineral determination and in aiding to classify rocks. In Chapter V, in which the methods for the identification of minerals are given, these tests and the proper ways of making them are fully described.

CHAPTER IV.

THE ROCK-MAKING MINERALS.

SEC. 1. *Primary Anhydrous Silicates and Oxides.*

THESE minerals from the geological standpoint are the most important in forming rocks. They are the most abundant and the most widely diffused. They are the chief minerals which are formed by the cooling and crystallization of the molten fluids of the earth's interior, and hence they are the main components of the igneous rocks. The greater part of the metamorphic rocks are also made up of them, and in the sedimentary beds they are also important constituents in many cases.

It is difficult to draw a sharp line between the absolutely anhydrous minerals and those containing considerable quantities of combined water. Thus, most hornblendes, micas and epidotes contain small amounts of hydroxyl and yet are ordinarily considered as anhydrous, compared, for instance, with kaolin, serpentine and chlorite. In the same way feldspar, hornblende and pyroxene are thought of as primary minerals although we know that in some cases they are of secondary origin, that is, they have been formed at the expense of previously existent minerals. The grouping as given is largely a matter of convenience; it includes those which are always anhydrous and always primary and which thus give a certain distinctive character to the group, which it is well to enforce, but it also includes many which are at times secondary and some which are hydrous, because on account of their mineralogic positions and affinities it is more convenient and natural to consider these minerals in this connection.

In the following section only such silicates and oxides are treated as are both hydrous and secondary.

a. Silicates.

The silicates are salts of various silicic acids, in which the hydrogen atoms have been replaced by various metals or radicals composed of metals in combination with oxygen, hydroxyl, fluorine, etc. The three important silicic acids which in this group form rock minerals are *polysilicic acid,* $H_4Si_3O_8$; *metasilicic acid,* H_2SiO_3, and *orthosilicic acid,* H_4SiO_4. The list of those treated as of importance on account of the functions which they have as rock-making minerals includes the feldspar, feldspathoid, mica, pyroxene, amphibole, olivine, garnet, tourmaline and epidote groups, and a few other less common ones.

FELDSPARS.

The term feldspar is not the name of a single mineral of a definite chemical composition like quartz, SiO_2, but is the designation of a group of minerals which have a general similarity in chemical and physical properties. They are indeed so much alike in general characters and appearance that in determining rocks by megascopic features they cannot be told apart except in special cases, and it is, therefore, best to treat them as a group, and at the same time mention those characters by which, when possible, they may be distinguished.

The rock-making feldspars are composed of three kinds and their mixtures as follows:

a. *Orthoclase,* $KAlSi_3O_8$, silicate of potash and alumina;
b. *Albite,* $NaAlSi_3O_8$, silicate of soda and alumina;
c. *Anorthite,* $CaAl_2Si_2O_8$, silicate of lime and alumina;
Alkalic feldspar, $(KNa)AlSi_3O_8$, mixtures of *a* and *b*;
Plagioclase feldspar, $(NaAlSi_3O_8)_x + (CaAl_2Si_2O_8)_y$, mixtures of *b* and *c*.

The simple feldspars are mostly confined to the crystals found in veins, druses, etc.; they sometimes occur as the component grains of rocks, but are comparatively rare; in the great majority of cases the feldspars are either mixtures of orthoclase and albite in varying proportions but usually with a considerable excess of the potash compound and are then called *alkalic* feldspar, or they are mixtures of albite and anorthite and are then known as soda-lime feldspar or *plagioclase*. All transitions from pure albite to pure anorthite occur, and the series has been divided into groups according to the different proportions of the soda and lime molecules; one of the most important of these is called *labradorite* in which there are about equal amounts of the two kinds.

Mixtures of *a* and *c*, of the potash and lime feldspars, have been found to occur but are so rare that for practical purposes they may be neglected.

Form. Orthoclase is monoclinic in symmetry, and when in distinct well-made crystals it commonly takes the forms shown in the accompanying figures. Sometimes the crystals are stout and thick in their habit or appearance as in Fig. 5, sometimes they are thin and tabular parallel to the face *b* as in Fig. 6, and again they may be rather long and columnar as in Fig. 7. In orthoclase the face *c* is always at right angles with the face *b*. In albite and anorthite, whose crystallization is

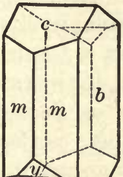


Fig. 5.

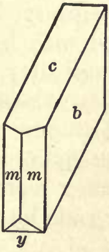


Fig. 6.

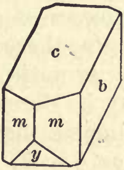


Fig. 7.

triclinic, these faces *c* and *b* are not at right angles but are slightly oblique; this is also true for all of their mixtures or the plagioclase group in general. Some mixtures of orthoclase and albite, as well as certain varieties of the pure potash compound $KAlSi_3O_8$ called *microcline,* are also slightly oblique, but in all these cases mentioned the amount of departure from a right angle is only a few degrees which, even under favorable conditions, can scarcely be perceived by the eye and must be measured by a goniometer to be appreciated. It cannot, therefore, under ordinary circumstances, be used as a means of discrimination between the alkalic and plagioclase feldspars. The forms of the crystals in which the plagioclase feldspars appear in rocks when they have the opportunity to crystallize freely are similar to those mentioned above for orthoclase in Figs. 5–7.

It is only in the phenocrysts of porphyritic igneous rocks and in the miarolitic druses of the massive igneous ones that these minerals have an opportunity to assume the free crystal forms described; in ordinary cases their crystallization is interfered with by other minerals or by other crystals of feldspar and they are thus seen in shapeless masses or grains. Nevertheless there is a tendency to assume these forms, and in some rocks, such, for instance, as the syenites, which are mainly composed of feldspar, it may be observed that they have more or less perfectly the shape of flat tables or rude laths as they approximate to Figs. 6 or 7.

Twinning. Crystals frequently appear compound, as if cut through parallel to some prominent plane on them and one of the halves revolved 180 degrees, usually on an axis perpendicular to the plane of division which is called the twinning plane, and the two parts grown together. Such an arrangement is called a twin crystal. Feldspars very commonly occur in twin crystals, one of the most frequent arrangements being that illustrated in Fig. 8 and known as the *Carlsbad* twinning from the town of that name in Bohemia where excellent examples have been found. It is as if a crystal like that shown in Fig. 5 were cut through parallel to the face *b*, one of the parts revolved 180 degrees around a vertical axis parallel to the edge *mb* and then joined and the two parts pushed together so that they mutually penetrate. In Fig. 9 the same arrangement is seen looking down on the face *b* of the crystal; *acya* is the outline of the original crystal; if this is cut out in a piece of paper and then turned over 180 degrees or upside down and laid on *acya* so that the edges *aa* are brought together, it will give the result seen in the figure. In the twin crystal illustrated in Fig. 8 the face *c* slopes toward the observer, the face *y* slopes away behind; in the twinned half this is reversed; as explained under the cleavage of feldspars this fact is of importance in helping to recognize these twins when the outward crystal form is imperfect or wanting. Carlsbad twins of the character described are found of all the different varieties of feldspar; they are most perfectly developed in the phenocrysts of the porphyritic igneous rocks, especially in the large orthoclase phenocrysts of some granite porphyries.

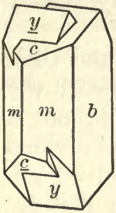


Fig. 8

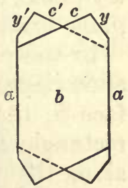


Fig. 9

In the Carlsbad twin the plane of division of the two parts is one parallel to the face *b*; the axis on which one part is revolved is the vertical line parallel to the edge *ab* of Fig. 10 and not one perpendicular to *b* or parallel to the edge *ac* which is usually the case in twinning, as already mentioned. The face *c* in orthoclase makes a right angle with *b*; the outline of the face *a* is, therefore, a rectangle, and if the crystal were divided along the dotted line by a plane parallel to *b* and one of the halves revolved 180 degrees on an axis

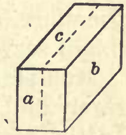


Fig. 10

parallel to the edge *ac*, that is, perpendicular to *b*, it would appear precisely as before and no twinning would occur. The crystallographic reason for this is that *b* is a symmetry plane, since the crystal is monoclinic, and a symmetry plane cannot be a twinning plane.

In the plagioclase group, in albite, anorthite and their admixtures, the face *c* makes an oblique angle with the face *b*; the face *a* is, therefore, a rhomboid and not a rectangle as shown in Fig. 11: if this crystal is divided along the dotted line and one of the halves revolved 180 degrees it will present the appearance seen in Fig, 12; the face *c* and the lower *c* now brought on top slope toward each other, forming a re-entrant angle, while below they produce a salient angle. A twin crystal is, therefore, produced, and this kind of twinning is known as the *albite* method because it is so generally found in that variety of feldspar. A complete crystal of this kind is seen in Fig. 13. The crystallographic reason that this can occur is because these feldspars are triclinic; they have, therefore, no symmetry plane, and any one of the faces might serve as a twinning plane.

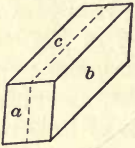


Fig. 11

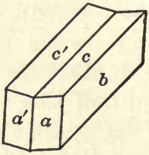


Fig. 12

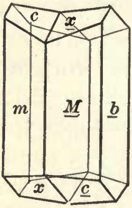


Fig. 13

Multiple Twinning. In nature, in actual practice, we rarely find a single albite twin of the kind described above. In the rock-making plagioclases the crystals are divided again and again into thin slices, and these are alternately twinned upon one another, producing the effect seen in Fig. 14. Indeed, this albite twinning descends to such a remarkable degree of fineness that the twin layers are less than the one hundred thousandth of an inch in thickness and are scarcely to be perceived in thin sections in polarized light under the highest powers of the microscope. It frequently happens, however, especially in those feldspars containing much lime, like labradorite, that it is coarse enough to be readily seen by the naked eye; one cleavage surface of such a feldspar appears as if ruled by fine parallel lines or striations as illustrated in Fig. 15. Even when very fine and on a small cleavage surface of a feldspar grain embedded in the rock, by a proper adjustment of the light reflected from the surface and the use of a good lens this multiple twinning may be distinctly seen.

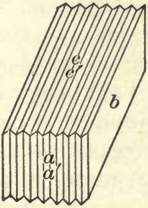


Fig. 14

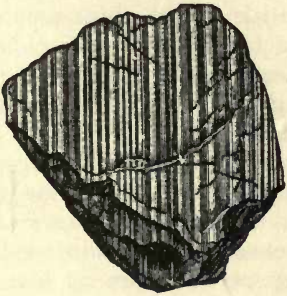


Fig. 15

Sometimes feldspars are twinned both according to the Carlsbad and the albite laws; they may be seen divided into the Carlsbad halves by the reflection of light from the cleavage and each of these ruled by the fine lines of albite twinning. An illustration of the combination of these two, each Carlsbad half divided into albite halves, is seen in Fig. 16. The practical use of the twinning of feldspars is explained in the paragraph on methods for their determination. Other methods of twinning beside those

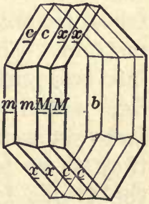


Fig. 16

mentioned occur in the feldspars, but in the megascopic study of rocks they are not of importance.

Cleavage. All the different varieties of feldspar are alike in possessing a good cleavage in two directions, one parallel to the face *c* and another parallel to *b* (see Fig. 7). Since in orthoclase these two faces intersect at a right angle, so also do the cleavages, and from this fact its name is derived (Greek, *ορθος*, straight, right + *κλᾶν*, to break); in the lime-soda feldspars, albite to anorthite, these faces are slightly oblique, and so are the cleavage planes; hence the name plagioclase (Greek, *πλάγιος*, oblique + *κλάν*, to break) has been given to the group.

In rocks, if the feldspar grains are of good size, the cleavages are readily seen by reflected light; they are commonly interrupted, giving rise to steplike appearances. Even when the grains are small the cleavage can usually be detected with a lens in good light. Sometimes when the feldspars are more or less altered, as described under alteration, they lose more or less completely their capacity for showing good cleavage faces on a broken surface of the rock, and this fact must be taken into account in making determinations. As in the crystals which show distinct faces, so in cleavage pieces, the amount of obliquity of the plagioclases is too small to be used in distinguishing them from right angled orthoclases by the eye or lens.

On a fractured rock surface if the crystal grains are of sufficient size the cleavages frequently permit one to recognize that they are twinned according to the Carlsbad method. The grain or broken crystal appears divided into two parts by a distinct line; on one side of this, if the line points away from the observer, the cleavage surfaces slope or step away in one direction; in the other half they slope towards the observer at an equal angle, like the two *c* faces in Fig. 8, to which indeed they are parallel. This can usually be readily seen by shifting the position of the surface in a good light until the cleavages reflect it. At the same time if examined with a good lens they may often be seen to be ruled by the fine parallel striations of the albite twinning, which indicates that the feldspar grain is a plagioclase.

Fracture. In directions in which they do not cleave the fracture of feldspars is uneven and sometimes somewhat conchoidal. They are brittle.

Color, Luster and Streak. Feldspars do not possess any natural color, hence, as explained under the color of minerals, they should normally be either limpid and colorless or white. Transparent, colorless, glassy feldspars in rocks are confined to fresh and recent lavas in which they may be frequently seen in the phenocrysts; they practically never occur in massive granular rocks like granites, gneisses, etc. In such lavas the luster may be strongly vitreous. More commonly they are semi-translucent or opaque and white, grayish white or yellowish and of a somewhat porcelain-like appearance. Orthoclase and the alkalic group of feldspars in general are very apt to have a tinge of red; this color varies from a pale flesh color to a strong brick-red or brownish red; a distinct flesh color is the shade most common. It is this which gives many granites used for building stones their color. It is most probable that this variety of color is caused by finely disseminated ferric oxide dust which acts as a pigment, and it must be considered as exotic and not a natural color. The plagioclases or lime-soda feldspars more rarely show this; they are commonly gray, and the difference between the two classes of feldspars is apparently due to a difference in the chemical behavior of iron towards soda and potash; soda enters readily into combination with iron in silicate minerals, while potash does not. Thus in the potash feldspars the iron would tend to be present as free oxide and color them. Therefore rocks with potassic feldspars often tend to be of reddish color, those with sodic feldspars tend to be gray. This distinction may be used to some extent as an indicator of the kinds of feldspar, but it must never be taken as an absolute rule, because many potassic feldspars are white or gray, and conversely many instances occur where rocks with soda-lime feldspars are red. In general one may say that if the rock contains two feldspars one of which is red while the other is not, it is almost certain that the red feldspar is a potassic one or orthoclase.

The potassic feldspars, especially the variety called microcline when occurring in distinct crystals in the miarolitic druses of granitic rocks, have sometimes a green color, pale to bright grass-green. This is also an exotic coloration and is supposed to be due to some organic substance acting as a pigment, since it disappears on heating.

Sometimes the rock feldspars are gray, dark, smoky or bluish-gray or even black. While this may happen with alkalic varieties, it is much more common with the soda-lime ones, especially labradorite. It is caused by a fine black dust disseminated through them which acts as a pigment and which may sometimes be magnetite dust, but is much more often ilmenite, — titanic iron ore. Fine examples of these are seen in the labradorite rocks from Canada, the Adirondack region in New York State and from Labrador which have been called anorthosites. Sometimes these inclusions are of sufficient size and so regularly arranged in the feldspar that, by the interference of light, they produce an opalescence or play of colors in the mineral as seen in the beautiful examples from St. Paul's Island on the coast of Labrador and from Kiev in Russia.

In other cases feldspars have a pearly bluish opalescence from innumerable minute cracks regularly arranged which reflect light with interference colors.

The *luster* is vitreous and on cleavages often pearly. Feldspars which are more or less altered often have a waxlike appearance and a waxy, glimmering luster; if completely altered they may look earthy and have no luster.

The *streak* is white and not characteristic.

Hardness. This is 6. Scratched by quartz, scratches glass, but is not scratched by the knife.

Specific Gravity. Orthoclase = 2.55, albite = 2.62, anorthite = 2.76. That of the various mixtures varies between these limits; thus the alkalic feldspars which consist of a mixture of orthoclase and albite average about 2.57, while the plagioclases vary regularly with the relative amounts of soda and lime, that of labradorite being 2.67. If the specific gravity of a fragment of feldspar can be taken with accuracy to the second place of decimals it affords a fairly good rough method of ascertaining its composition.

Chemical Composition. This is shown in the following table.

	SiO_2	Al_2O_3	CaO	Na_2O	K_2O	Total.
I	64.7	18.4	...	...	16.9	100
II	68.7	19.5	...	11.8	...	100
III	43.2	36.7	20.1	...	...	100
IV	55.6	28.3	10.4	5.7	...	100
V	66.7	18.9	...	5.7	8.7	100

I, Orthoclase (and microcline); II, Albite; III, Anorthite; IV, Labradorite (equal mixture of albite and anorthite); V, Alkalic feldspar (equal mixture of orthoclase and albite).

The mixtures vary naturally with the proportions of the pure products; examples of equal parts are given in IV and V. The other substances, such as iron oxide, etc., shown in feldspars by chemical analyses, are due to impurities.

Blowpipe and Chemical Characters. A fine splinter fuses before the blowpipe with difficulty to a globular ending, more easily with anorthite and the varieties rich in lime than with albite and orthoclase. The flame shows the persistent yellow coloration of soda; only occasionally in the rock feldspars does orthoclase occur, which is pure enough to give the violet flame of potash. Orthoclase and albite are not acted upon by ordinary acids to an appreciable extent; as the feldspars increase in lime they become more soluble, thus labradorite is very slowly dissolved while anorthite is slowly dissolved and affords gelatinous silica.

Alteration. Under the action of various agencies the feldspars are prone to alter into other substances, which depend in part on the nature of the agents and in part on the composition of the feldspar attacked. Some of these changes and products are quite complex and their nature and significance have not as yet been sufficiently studied for us to understand them, but some of the simpler and more important ones are as follows.

When the feldspars are acted upon by water carrying carbonic acid gas in solution, which may be the case in surface waters leaching downward or in hot waters rising from depths below, they may be turned into kaolin or muscovite with separation of free silica and alkaline carbonates. These changes may be expressed chemically as follows.

Orthoclase + Water + Carb. diox. = Kaolin + Quartz + Potas. Carb.
$2\,KAlSi_3O_8 + 2\,H_2O + CO_2 = H_4Al_2Si_2O_9 + 4\,SiO_2 + K_2CO_3$
Orthoclase + Water + Carb. diox. = Muscovite + Quartz. + Potas. Carb.
$3\,KAlSi_3O_8 + H_2O + CO_2 = H_2K(AlSiO_4)_3 + 6\,SiO_2 + K_2CO_3$

What determines whether the removal of the potash from the feldspar will be complete so that kaolin is formed or only partial so that muscovite is the resultant product is not clearly understood. In a general way one may say that weathering from the action of surface waters generally forms kaolin while the change to muscovite is more apt to be a deep-seated affair and is especially noted in processes of metamorphism. In mines it is often seen that the solutions which deposited the ores have altered the rocks enclosing them, sometimes to kaolin, sometimes to a form of muscovite (sericite) and sometimes to other products. It is due to this in great part that such rocks are so often changed from their original fresh condition.

All feldspars undergo similar changes to those mentioned, but in those which contain lime they are more complex, as calcite, the carbonate of lime is also formed. Accordingly, as this change to muscovite or kaolin is more or less complete, the feldspars lose their original bright appearance and become dull and earthy in character; if it is pronounced they are soft and may be cut or scratched with the knife or even with the finger nail. In certain changes in the lime-soda feldspars they have a faint, glimmering luster, are semi-translucent, often of a pale bluish or grayish tone, lose to a great extent their property of cleavage and resemble wax or paraffin as mentioned under cleavage. Often these changes do not take place regularly through the whole mass of the crystal, sometimes the border is altered, sometimes the center only is attacked and sometimes, especially in the lime-soda ones, like labradorite, zones between the two are altered. If the feldspars of a rock do not show bright, glistening cleavage surfaces it may be considered practically certain that they are more or less altered. These alterations of the feldspars are of great importance in geologic processes and especially in the formation of soils.

In addition to these alterations others are also known, thus under some circumstances the feldspars are changed into zeolites and in metamorphic processes those containing lime may take part with other minerals in forming epidote, garnet, etc., changes which are mentioned elsewhere.

Occurrence. The feldspars are of wide distribution, perhaps more so than any other group of minerals. They are found in all classes of rocks, in most of the igneous ones, such as granites, syenites, porphyries and felsite lavas; in the sedimentary ones in certain kinds of sandstones and conglomerates and in the metamorphic rocks in gneisses. Since, so far as our knowledge extends,the crust of the earth, underlying all the sedimentary beds of all ages deposited upon it, is composed chiefly of granites, gneisses, etc., in which feldspars are the main minerals, it is not too much, perhaps, to say that there is more feldspar in the world than any other substance of whose occurrence we have knowledge.

Determination. In general, the two cleavages at right angles or nearly so, the vitreous luster, light color and hardness, which resists the point of the knife, enable one in the field to recognize the feldspar grains of rocks and to distinguish them from the other common minerals, especially quartz, with which they are usually associated. Sometimes the crystal form may also be of assistance, especially in porphyries. In addition one or more of the various chemical and physical properties enumerated above may be determined on separated fragments, if the feldspar grains or masses are of sufficient size.

The determining of the different varieties of feldspar which may be present in a rock is, however, a much more difficult task when only megascopic means are employed. Sometimes the remarks made under the heading of color will be of assistance. If the cleavage surfaces are closely examined with a lens and the fine lines of striation of the albite twinning are found then one knows that a plagioclase feldspar is present, since orthoclase cannot have this twinning as previously explained. The only practical exception to this rule is that the large, often huge, crystals of potash feldspar found in granite-pegmatite dikes are often not really orthoclase but microcline, a triclinic variety and a good cleavage surface of this examined in a strong light with a powerful lens frequently shows a minute, scarcely perceptible, multiple twinning like the albite twinning.

If no multiple twinning is seen it would not be, therefore, safe to conclude that the feldspar is necessarily an orthoclase or alkalic variety and not a plagioclase because this twinning, as already stated, is often so fine that it cannot be detected with the lens and is sometimes wanting. As the grain of rocks grows finer it becomes increasingly difficult to detect, but a good training of the eye by studying a series of rocks in which it is present in the feldspars is a great help and eventually enables one to perceive it clearly in cases where at first it could not be seen. The modern tendency on the part of geologists to refer all difficulties in rocks to microscopic examination of thin sections has led to a great neglect in the training of the eye for megascopic determination of minerals in rocks with a corresponding loss of efficiency in the field.

If the albite twinning is clearly seen in several of the feldspar grains of a rock it may be quite safely concluded that a considerable proportion of plagioclase is present and this may indeed be practically the only feldspar present. If it cannot be seen plagioclase may or may not be present.

Other means which may be resorted to are the determination of the specific gravity, the behavior before the blowpipe, and with acids, as previously mentioned, and the chemical tests for soda, potash and lime, which suggest themselves to those experienced in analytical chemistry. Further information in the subject should be sought in the special manuals devoted to determinative mineralogy.

THE FELDSPATHOID GROUP.

The feldspathoid group owes its name to the fact, that, like the feldspars, it is composed of minerals which are silicates of alumina with soda, potash and lime and that they are found in the same associations, accompanying or replacing feldspars and playing a similar function in the making of rocks. Unlike feldspars they are comparatively rare and are restricted entirely to certain kinds of igneous rocks such as nephelite syenite. Thus in treating of the occurrence of common rocks they are, compared with the feldspars, of relatively much less importance, but, in dealing with questions regarding the origin of igneous rocks, they are of great significance. The more important members of the group are *nephelite* and *sodalite,* less common ones are *noselite* and *hauynite, cancrinite* and *leucite.*

Nephelite. This mineral crystallizes in short, thick, hexagonal prisms or tables with a flat base and top but it rarely shows distinct crystal form in rocks. Most commonly it occurs in shapeless masses and grains like quartz. Its normal color is white, but it is usually gray, varying from light smoky to dark in tone, sometimes it is flesh colored or brick-red. The white color may shade into yellowish, the gray into bluish or greenish. Streak, light — not characteristic. Translucent. Its luster, when fresh, is oily or greasy and much like that of quartz and, like this mineral, it has no good cleavage and its fracture is somewhat conchoidal. Brittle. Hardness, nearly that of feldspar = 6. Specific gravity, 2.55–2.61. Its composition is chiefly $NaAlSiO_4$ with a small varying amount of potash replacing soda. Before the blowpipe a fine splinter fuses quite readily to a globule tingeing the flame deep yellow. Readily soluble in dilute acid with formation of gelatinous silica.

Sodalite. The form of crystallization is the isometric dodecahedron, so often seen in garnet, but this rarely occurs in rocks, the mineral commonly occurring in formless grains and lumps. It is sometimes white, pink, or greenish gray, but the usual color is a blue of some shade, often a bright sky-blue to dark rich blue. The blue color may be due to a slight admixture of the lapis-lazuli molecule acting as a pigment. Usually translucent. Cleavage dodecahedral but not striking as a megascopic property; fracture uneven to poorly conchoidal. Luster vitreous to greasy. Streak, white. Hardness nearly that of feldspar, 5.5–6. Specific gravity, 2.15–2.30. Its composition is $Na_4(AlCl)Al_2(SiO_4)_3$ and this may also be expressed $3\ NaAlSiO_4 . NaCl$, but it should not be understood from this that it consists of a mixture of nephelite and common salt molecules; it is a definite chemical compound into which the chlorine enters. Fuses rather easily before the blowpipe with bubbling, coloring the flame yellow. Easily soluble in dilute acids with formation of gelatinous silica; in the nitric acid solution chlorine may be tested for with silver nitrate.

The other feldspathoids are less common and in their general properties, modes of occurrence and functions as rock minerals are similar to nephelite and sodalite, which they are usually found associated with or in part replacing in those rocks in which they occur.

Hauynite and Noselite. These show characters like sodalite but they differ from it in containing the radical SO_3 of sulphuric acid in the place of chlorine and the best method of detecting them is by the test for sulphuric acid with barium chloride in their nitric acid solution. They differ from one another only that in hauynite a part of the soda is replaced by lime while noselite is the pure soda compound. *Cancrinite* is much like nephelite in its general properties, it contains CO_2 in combination, which affords aid in detecting it as explained later in testing minerals and rocks; its formula might be written $8\,NaAlSiO_4 . CaCO_3 . CO_2 . 3\,H_2O$, but as in sodalite it is not a mixture of molecules but a definite compound. The color is variable but frequently a bright yellow to orange which may also help in detecting it. It is supposed at times to be caused by the alteration of nephelite, but in most cases, if not always, it is an original mineral crystallizing from a molten magma, like nephelite and feldspar.

Leucite is a rare feldspathoid crystallizing in isometric trapezohedrons, a form illustrated in garnet; the crystals when imperfect appear spherical. Its cleavage is imperfect; fracture conchoidal; color white to gray; luster vitreous. Hardness is 5.5–6; specific gravity, 2.5. Before the blowpipe it is infusible and when mixed with powdered gypsum gives the flame the violet color of potassium. It dissolves in acids without gelatinizing. Its composition is $KAl(SiO_3)_2$. It occurs almost wholly in lavas and is nowhere common except in those of central Italy, where the magmas are characterized by a high content of potash. The most noted occurrence is in the lavas of Vesuvius, in some of which it is found in good-sized, well-shaped crystals of the form illustrated in Fig. 31 under garnet. Large crystals, altered, however, to other minerals, have been found in certain syenites and related rocks in Arkansas, Montana, Brazil and elsewhere.

Alteration. The feldspathoids, like the feldspars, are liable to alteration from the processes of weathering when exposed to the atmosphere and to the action of fluids circulating in the rocks at lower levels. They become converted into kaolin or muscovite and also very commonly into zeolites. The latter case is very general; all that is necessary is a rearrangement of the molecule and the assumption of water and silica; hence when the feldspathoids are heated in a closed glass tube they are very apt to yield water. Thus

$$\begin{array}{ccccccc} \text{Nephelite and} & \text{silica and} & \text{water} & \text{yield} & \text{analcite.} \\ NaAlSiO_4 + & SiO_2 + & H_2O & = & NaAl(SiO_3)_2 . H_2O. \end{array}$$

The *determination* of the feldspathoids in rocks is best done by chemical means. With the exception of leucite, which is too rare a mineral to be considered except in very unusual cases, they yield gelatinous silica and may be tested for as described later under mineral tests. Nephelite is easily confused with quartz which it often closely resembles in rocks; its association with other minerals and the appearances of those rocks in which it chiefly occurs and which are described in their appropriate places, helps in arousing suspicion of its presence and this is readily confirmed by its solubility in acids. Fortunately for field determinations nephelite is a very rare mineral, quartz an exceedingly common one; thus the assumption that the mineral is quartz in the vast majority of cases will be right.

MICAS.

The micas form a natural group of rock minerals, which is characterized by great perfection of cleavage in one direction, and by the thinness, toughness and flexibility of the elastic plates or laminæ into which this cleavage permits them to be split. For practical purposes of megascopic rock study and classification they can be divided into two main groups, *light* colored micas or *muscovite* and related varieties, and *dark* colored *biotite* and related varieties.

Form. Micas crystallize in six-sided tablets with flat bases; they appear to be short hexagonal prisms, (see Fig. 17); in reality, as may be shown by optical methods, their crystallization is monoclinic. Their side faces are rough and striated, the flat bases, which are usually cleavage faces, bright and glittering. Sometimes two of the side faces are much elongated, as in Fig. 18. While distinct crystal form is often observed in rocks, particularly the igneous ones, the micas are much more commonly seen in shapeless flakes, scales or shreds, with flat, shining, cleavage faces. Sometimes the foliæ or leaves are curled or bent.

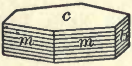


Fig. 17

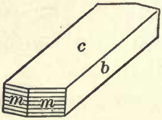


Fig. 18

Cleavage. This has been already mentioned. It is perfect parallel to the base and it is this property combined with its flexibility, transparency and toughness that makes the large crystals and sheets of muscovite found in pegmatite veins so useful in making stove windows, lamp chimneys, etc., where ordinary glass is easily broken. Sometimes when the mineral occurs in an aggregate of minute scales, especially muscovite in the sericite form, the cleavage is not so apparent, but can generally be seen by close observation.

Color, Luster and Hardness. Muscovite is colorless, white to gray or light brown, often with greenish tones. The other light-colored micas are similar, except that lithia mica or lepidolite, found in pegmatite veins, is usually pink or lilac colored. These micas in thin sheets are transparent.

Biotite and its congeners are black, in thin sheets translucent with strong brown, red-brown or deep green colors. The phlogopite variety is pale brown, sometimes coppery. The luster of micas is splendent, on cleavage faces sometimes pearly and in the sericite variety of muscovite frequently silky. The hardness varies from 2–3; all are easily scratched with the knife.

Chemical Composition. Chemically the micas which take part in rock-making may be divided into two main groups, one containing iron and magnesia, of which the dark-colored biotite is an example, the other devoid of these oxides, of which muscovite is the most prominent member. They are complex in composition, silicates of alumina with alkalies and containing more or less hydroxyl and fluorine. The two main varieties may be represented as follows:

$$\begin{aligned} &\text{Muscovite} = H_2KAl_3(SiO_4)_3. \\ &\text{Biotite} \quad\;\; = (HK)_2(Mg\overset{..}{Fe})_2(Al\overset{...}{Fe})_2(SiO_4)_3. \end{aligned}$$

The other members of the muscovite group are, *paragonite*, a rare mineral like muscovite, in which soda replaces potash and *lepidolite,* in which the potash of muscovite is partly replaced by lithia. In the biotite sub-group, *phlogopite* is a variety nearly free from iron and thus a magnesia mica; the lack of iron accounts for its lighter color; *lepidomelane,* on the contrary, is very rich in iron, especially ferric oxide, while another, *zinnwaldite,* contains some lithia in place of part of the potash. The formulas of these compounds are very complex and in part not absolutely settled. The adjoining table of analyses shows the chemical differences between the varieties.

	I	II	III	IV	V	VI	VII
SiO_2	44.6	46.8	48.8	36.0	39.6	32.1	45.9
Al_2O_3	35.7	40.1	28.3	18.8	17.0	18.5	22.5
Fe_2O_3	1.0	—	0.3	5.6	0.3	19.5	0.6
FeO	1.0	—	0.1	14.7	0.2	14.1	11.6
MgO	—	0.6	—	9.8	26.5	1.0	—
CaO	0.1	1.3	0.1	0.6	—	—	—
Na_2O	2.4	6.4	0.7	0.4	0.6	1.5	—
K_2O	9.8	—	12.2	9.3	10.0	8.1	10.5
Li_2O	—	—	4.5	—	—	—	3.3
H_2O	5.5	4.8	1.7	2.5	3.0	4.6	0.9
F	0.7	—	5.0	0.3	2.2	—	7.9
X*	—	—	—	1.9	1.2	1.4	1.7
Total	100.8	100.0	101.7	99.9	100.6	100.8	104.9

* X represents small quantities of non-essential oxides present.

I, Muscovite, Auburn, Me.; II, Paragonite, the Alps; III, Lepidolite, Hebron. Me.; IV, Biotite, from granite, Yosemite, Cal.; V, Phlogopite, Burgess, Ontario; VI, Lepidomelane, from nephelite syenite, Litchfield, Me.; VII, Zinnwaldite, Zinnwald, Erzgebirge.

Blowpipe and Chemical Characters. Usually the micas whiten before the blowpipe and fuse on the edges, when in thin scales. Lepidomelane fuses to a black magnetic globule. Heated in the closed glass tube they yield very little water, which helps to distinguish them from chlorites and other micaceous rock minerals. When thin scales are treated with a little boiling concentrated sulphuric acid in a test tube, muscovite and the related light-colored kinds are scarcely acted upon, but biotite and its congeners are decomposed, the scales losing their luster and transparency while the acid becomes turbid.*

Lepidomelane is soluble in hydrochloric acid, depositing silica in scales, an important character serving to distinguish it from the other micas. The lithia micas impart a red color to the blowpipe flame, paragonite the yellow color of sodium.

Alteration. Biotite under the action of weathering changes to chlorite, loses its elasticity and becomes soft and of a green color. Muscovite being itself often the product of various alterations of other minerals, especially of feldspars, appears well fitted to withstand the process of weathering and its scales often occur in soils made of broken-down rocks whose other constituents may be greatly changed. It eventually changes, loses its transparency and elasticity and perhaps becomes ultimately converted into clay.

Occurrence. The common micas are minerals of wide distribution as rock components. *Biotite* is a very common and prominent ingredient of many igneous rocks, especially of those rich in feldspar like granites and syenites — in ferro-magnesian rocks like gabbro it is less prominent; it is also seen in many felsite lavas and porphyries. It occurs commonly in some metamorphic rocks such as gneisses and schists and is frequently one of the products of contact metamorphism of igneous rocks. From its liability to alteration it does not figure as a component of sedimentary beds. The *phlogopite* variety containing little iron has been found in some rare cases in

---

* Care should be used in making this test not to bring the hot acid in contact with water, or the mixture will take place with explosive activity.

igneous rocks, but it chiefly occurs as a product of metamorphism in crystalline limestones or impure marbles and dolomites. *Lepidomelane* and *zinnwaldite* appear to occur chiefly in granites and syenites, especially in pegmatitic varieties. *Muscovite* occurs in granites and syenites, especially in pegmatite veins and in miarolitic druses and in places where the igneous rocks have been subjected to later fumarole actions furnishing water and fluorine. It is sometimes seen in intrusive porphyries and lavas of felsitic character. It is especially common in the metamorphic rocks and is widely distributed in gneisses and schists; sometimes, especially in the latter rocks, it is in the form of an aggregate of minute scales which have a silky luster and largely lack in appearance the evident characters of the mineral, such as its cleavage; this variety has been called *sericite.* When feldspars are altered to muscovite, rather than to kaolin, this sericite variety is the common product. In the sedimentary rocks, such as conglomerates and sandstones, muscovite is sometimes seen, an unchanged remnant of the original rocks from which their material came. *Lepidolite* is practically restricted to granite-pegmatite veins and is constantly accompanied by tourmaline. *Paragonite* has been found in only a few cases, in schists, playing the rôle muscovite would ordinarily have.

Determination. From the ordinary rock minerals the micas are at once distinguished by their appearance, high luster and eminent cleavage, the latter quality and their hardness being readily tested in the field by the knife point. From the chlorite group and from talc, which resemble them, they are told by the elasticity of their split-off laminæ, those of the chlorites and talc being flexible but not elastic. From *chloritoid* a micaceous appearing mineral of a gray or green color, a hydrated silicate of alumina, magnesia and iron, which is sometimes seen in distinct crystals in certain metamorphic rocks, they are readily distinguished by its superior hardness = 6.5

and brittleness. The different varieties of mica are best discriminated by the chemical and blowpipe tests already mentioned.

PYROXENES.

The pyroxene group embraces a number of important minerals which have in common the fact that they are metasilicates, salts of metasilicic acid, H_2SiO_3, in which the hydrogen is replaced by various metals as shown later, and although they may differ in the system in which they crystallize, in having closely related crystal form, notably a prismatic cleavage of 87 and 93 degrees. As rock minerals they are of greatest importance in the igneous rocks though they may be prominent at times in some of the metamorphic ones. Some igneous rocks are composed almost entirely of pyroxene.

It is often difficult to recognize pyroxene in the rocks and distinguish it from several other minerals purely by simple megascopic methods and largely impossible to tell from one another by such means the many varieties recognized by mineralogists and petrographers. The differences between these varieties are chiefly in chemical composition and optical properties and these must be determined by chemical and optical methods.

For practical megascopic petrography the pyroxenes may be divided into the following sub-groups dependent on their color, behavior before the blowpipe and chemical reaction for lime as described later: *hypersthene*, *diopside*, *common pyroxene*, *augite* and *aegirite*.

Form. Hypersthene crystallizes in the orthorhombic, the others in the monoclinic systems, but this distinction is not a matter of practical importance in megascopic work, since the former is rarely well enough crystallized to determine the system. The common form, in which the monoclinic rock pyroxenes crystallize, is a prism, usually short and thick though sometimes longer and more slender. Such a prism is shown in Fig. 19, the ends modified by pyramidal faces. Generally, however, the edges of the prism *mm* are truncated by a front face *a* and a side face *b* — sometimes these truncations are small so that *a* and *b* are slender (Fig. 20); often they are very broad and *mm* narrow. While these faces are commonly well developed and often lustrous the pyramidal faces are often very imperfect or wanting, the crystal being rounded at the ends; rarely other pyramidal faces are present and the ends much more complex than in the figures. The augites which occur in igneous rocks, especially porphyries and lavas, very often have the appearance and development shown in Fig. 21. The most important thing in the crystallization is that the angle *m* on *m* is nearly a right angle, 87 degrees, so that the prism is nearly square in cross section or when truncated by *a* and *b*, octagonal as shown in Fig. 22. Besides occurring in prismatic crystals the pyroxenes also are very common in grains, or in more or less shapeless masses; this is

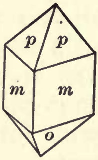


Fig. 19

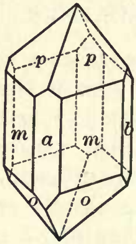


Fig. 20

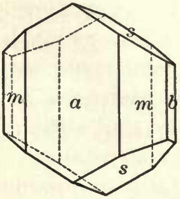


Fig. 21

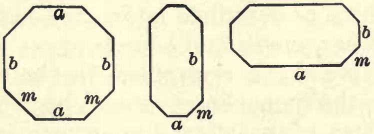


Fig. 22

usually the case in certain massive igneous rocks such as gabbros and peridotites.

Cleavage and Fracture. As previously mentioned the pyroxenes have a cleavage parallel to the faces *mm*, nearly at right angles as shown in Fig. 23; this is fundamental and serves to distinguish the mineral from hornblendes. This cleavage is usually very good but not perfect. Some varieties often have a good parting in other directions resembling cleavage which causes the mineral to appear lamellar, perhaps even somewhat micaceous, as seen in the pyroxenes of some gabbros. Fracture uneven; the mineral is brittle.

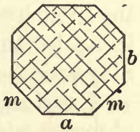


Fig. 23

Color and Luster. The color varies from white through various shades of green to black, according to the amount of iron present. The pure diopsides are white, rarely colorless and transparent, often pale green, and more or less translucent; common pyroxenes are dull green of various shades; augite and aegirite are black; these are opaque. The luster, which is often wanting, is glassy to resinous. Streak varies from white to gray-green.

Hardness and Specific Gravity. The hardness varies from 5–6. Some varieties can be just scratched by the knife. The specific gravity varies, chiefly with the iron present, from 3.2–3.6.

Chemical Composition. Pyroxenes are composed of the metasilicate molecules $MgSiO_3$, $\ddot{F}eSiO_3$, $CaMg(SiO_3)_2$, $Ca\ddot{F}e(SiO_3)_2$, $Na\dddot{F}e(SiO_3)_2$ and $\ddot{R}\dddot{R}_2SiO_6$ in which last $\ddot{R} = Mg\ddot{F}e$ and $\dddot{R} = Al$ and $\dddot{F}e$. These molecules are *isomorphous*, that is, capable of crystallizing in various mixtures which produce the same crystal form and many similar physical properties. The *hypersthene* sub-group contains mixtures of $MgSiO_3$ and $FeSiO_3$ without lime; *diopside* is $CaMg(SiO_3)_2$ with little or none of the iron molecule, *common pyroxene* contains variable mixtures of $CaMg(SiO_3)_2$ (diopside) and $CaFe(SiO_3)_2$ (hedenbergite) with small portions of the other molecules; *augite* contains the same but in addition a large amount of $\ddot{R}\dddot{R}_2SiO_6$; *aegirite* is mostly $Na\dddot{F}e(SiO_3)_2$ and is thus a soda pyroxene.

Blowpipe and Chemical Characters. Hypersthene varies from almost infusible in the blowpipe flame when containing little iron (variety enstatite) to difficultly so with much iron; in the latter case it becomes black and slightly magnetic. The other pyroxenes are much more fusible = 4 and melt quietly or with little intumescence to glassy globules whose color depends on the amount of iron, diopside nearly colorless, common pyroxene green or brown, augite and aegirite black; the last two magnetic. Aegirite fuses quietly and colors the flame yellow. They are but slightly acted upon by acids, those with iron more so than those without.

These differences in the chemical composition are shown in the table of analyses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	X*	Total.
I .	53.1	1.0	...	17.8	24.8	2.7	...	0.4	99.8
II .	58.0	1.3	...	3.1	36.9	...	...	0.8	100.1
III	55.1	0.4	...	1.1	18.1	25.0	0.4	0.2	100.3
IV.	51.1	2.0	1.3	12.3	10.0	22.1	...	0.4	99.2
V .	47.0	9.8	4.5	4.1	16.0	19.0	...	...	100.4
VI.	51.4	1.8	23.3	9.4	0.3	2.0	11.9	0.1	100.2

* X = small quantities of other oxides.

I, Hypersthene, Romsaas, Norway; II, Hypersthene (var. enstatite), Bamle, Norway; III, Diopside, DeKalb, N. Y.; IV, Common pyroxene, Edenville, N. Y.; V, Black augite, Vesuvius lava; VI, Aegirite, from syenite, Hot Springs, Ark.

Alteration. The pyroxenes are prone to alter into other substances whose nature depends partly on the kind of process to which they are subjected and partly on their own composition. Thus under the action of weathering they may be converted, if containing much magnesia, into serpentine, or into chlorite, if containing iron, or into both and often carbonates are also formed, such as calcite. Those containing much iron may completely break down into hydrated iron oxides, such as limonite, and carbonates.

Another very important change is one which they suffer under metamorphic processes, especially regional ones. In this they become altered to masses of fibrous, felty or stringy hornblende needles and prisms, usually of distinct but variable green colors. This process is of great geologic importance for by means of it whole masses of pyroxenic rocks, generally of igneous origin, such as gabbros, peridotites, basalts, etc., have been changed into hornblendic ones to which a variety of names, such as greenstone, greenstone schist, hornblende schist, etc., have been applied. The process is further mentioned under metamorphism, and under gabbro, dolerite, greenstone and amphibolite.

Occurrence. The pyroxenes are chiefly found in igneous rocks, especially those which are formed from magmas rich in lime, iron and magnesia. Therefore, in the dark colored rocks of this class they should always be looked for. They are not often found in igneous rocks which contain much quartz, hence in granites, felsite porphyries and felsite lavas they are rare. Augite is found in basaltic lavas and dark, trap-like intrusives, often in well formed crystals; when it occurs in gabbros and peridotites it is commonly in grains and lumps. Hypersthene is prominent in masses and grains in some varieties of gabbro and peridotite. Aegirite occurs chiefly in nephelite syenites and the phonolite variety of felsite lava. Some normal syenites and related rocks contain diopside-like or common pyroxene. In the metamorphic rocks common pyroxene and diopside, the latter sometimes white or pale greenish and transparent, are found in impure recrystallized limestones and dolomites, sometimes in well formed scattered crystals, sometimes aggregated into large masses. Common pyroxene also occurs in some gneisses. Being readily decomposed by weathering they play no part in sedimentary beds.

Determination. If the mineral under examination is in well formed crystals careful observation will usually show if it is a pyroxene by its possession of the forms previously described. The outline of the section presented by the prisms, especially when broken across, should be noted in this connection. The common minerals in rocks with which pyroxenes may be confused are hornblende, epidote and tourmaline. The lack of good cleavage, the superior hardness, the high luster, dense black color and triangular shape of the prism cross section of tourmaline readily distinguish it from pyroxene. Epidote has one perfect cleavage, one poor one; it is much harder, 6-7; while green it commonly has a yellow tone, giving a yellowish green; before the blowpipe it intumesces when fusing. The distinction of pyroxene from hornblende is more difficult and is treated under the head of that mineral.

To distinguish the different varieties of pyroxene from one another the blowpipe tests previously mentioned should be used in conjunction with the natural color of the mineral. The hypersthenes are most certainly told from other pyroxenes by making a chemical test to prove the absence of lime or at least its presence in only minute quantity. This is best done by making a small fusion with soda as described in the chapter treating of mineral tests.

AMPHIBOLES (HORNBLENDES).

The amphiboles, or hornblendes, names which are used interchangeably, are a natural group of silicate minerals which like the pyroxenes are salts of metasilicic acid H_2SiO_3, in which the hydrogen is replaced by various metals or radicals. They have in common a certain crystal form, a prismatic cleavage of about 55 degrees, and are nearly related in many physical properties. As in the pyroxene group, to which the amphiboles are closely allied in several ways, there are many varieties recognized by petrographers, dependent upon differences in chemical composition and physical properties, especially optical ones, which are impossible to distinguish by the eye and many of them indeed by ordinary megascopic tests.

For practical work in megascopic petrography the amphiboles may be divided into the following sub-groups: *Tremolite*, *Actinolite*, *Common Hornblende*, and *Arfvedsonite*. These may be distinguished by their colors, associations and behavior before the blowpipe.

Form. Amphiboles crystallize in the monoclinic system. The crystals are usually long and bladed, formed by two prisms *mm* which meet at angles of 55 and 125 degrees. Sometimes there are terminal faces *rr* as in Fig. 24, sometimes the crystals are imperfect at the ends and no terminal faces are seen; this latter is common in rocks. Very often the side face *b* is present truncating the prism edge and the crystal has a nearly hexagonal cross section as in Fig. 25. More rarely the front face *a* is present as in Fig. 26. The black hornblendes found as phenocrysts in some basaltic rocks have often a not very short prism and appear as in Fig. 27; these are the hornblendes which most often have distinct terminal planes. The prismatic faces *mm* and the face *b*, if it is present, are apt to be shining, the ends are frequently dull. It is not common

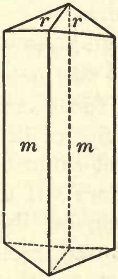


Fig. 24

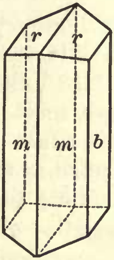


Fig. 25

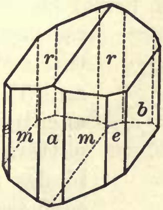


Fig. 26

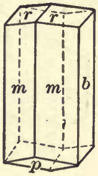


Fig. 27

for amphibole to present itself in rocks in crystals whose planes can be distinctly seen; when this occurs it is mostly with the black hornblendes found in lavas as phenocrysts and in those which occur in limestones and dolomites which have been subjected to metamorphism. The common appearance is in long slender blades with irregular, rough ends; this is usual in the hornblende schists where the crystals are aggregated together in more or less parallel position; they may dwindle in size to shining needles, becoming so fine that the minute prisms can hardly be seen with the lens; the aggregate then has a silky appearance. In the felsitic lavas and porphyries the prisms of the hornblende phenocrysts vary from rather short, like those in the figures, to slender needles; in the massive doleritic rocks like diorite the amphibole is apt to occur in irregular grains and small masses. Sometimes as in *asbestus* the mineral has a highly developed columnar, fibrous form.

Cleavage. Amphiboles have a highly perfect cleavage parallel to the prism faces *mm* as illustrated in the cross section, Fig. 28. Like the faces *mm* these cleavages meet at angles of 125 and 55 degrees, a fact of great importance in distinguishing the mineral. The glittering prismatic faces seen on the blades and needles of fractured rock surfaces are commonly due to this good cleavage. The fracture is uneven.

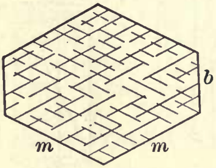


Fig. 28

Color and Luster. The color varies with the amount of iron from white or gray in tremolite to gray-green or bright green in actinolite to darker greens and black in common hornblende. Arfvedsonite is black. Some varieties found in igneous rocks which appear black are really deep brown. The mineral varies from opaque in the deeper colored varieties to translucent in the lighter ones. The luster is bright and vitreous to somewhat pearly on the cleavage surfaces; in very fine needle-like or fibrous varieties, silky. Streak, white to gray-green or brownish.

Hardness and Specific Gravity. The hardness varies from 5–6; some specimens can be scratched with the knife. The specific gravity varies, chiefly with the amount of iron, from 2.9–3.5.

Chemical Composition. Amphiboles like the pyroxenes are metasilicates, salts of H_2SiO_3, in which the hydrogen atoms are replaced by calcium, magnesium, iron, soda and also, as shown by Penfield, by radicals in which alumina plays a prominent part and which contain hydroxyl (— OH) and fluorine. Penfield has also shown that when calcium is present it replaces one fourth of the hydrogen atoms. Thus, while the amphiboles resemble the pyroxenes in being metasilicates and composed of the same elements, they differ from them in being much more complex and in containing hydroxyl and fluorine. Their compositions, as a rule, are too complicated to be represented by simple formulas, but in a general way, disregarding the hydroxyl and fluorine, one may say that each type of pyroxene has a corresponding amphibole and in this connection the composition of the pyroxenes should be studied.

Thus *tremolite,* if simply represented by $CaMg_3(SiO_3)_4$ corresponds to diopside $CaMg(SiO_3)_2$: while *actinolite,*

$$Ca(Mg\ddot{F}e)_3(SiO_3)_4,$$

with variable amounts of ferrous iron replacing magnesium corresponds to common pyroxene, $Ca(MgFe)(SiO_3)_2$; *common hornblende* or *hornblende* for short which consists of the actinolite molecule with others in which radicals containing alumina or ferric iron and usually both are present and perhaps some alkalies, corresponds in general to augite which is a variable mixture of pyroxene molecules with alumina and ferric iron; *arfvedsonite,* which contains chiefly soda, lime and ferrous iron, plays the part of aegirite, the soda iron pyroxene, though a very rare variety, riebeckite, more nearly corresponds in composition.

Glaucophane is a rare variety, consisting of a mixture of a soda-alumina molecule with a hypersthene molecule,

$$NaAl(SiO_3)_2 \,.\, (FeMg)SiO_3.$$

It is distinguished from other hornblendes by its blue color, often a rich sky-blue or lavender-blue. It occurs only in a rare variety of hornblende-schists, called glaucophane-schists, which are described under amphibolites.

The chemical composition is illustrated in the following table of analyses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	H_2O	F_2	XyO*	Total
I	57.5	1.3	0.2	0.2	24.9	12.8	0.7	1.3	0.8	0.6	100.3
II	56.1	1.2	0.8	5.5	21.2	12.1	0.2	1.9	0.1	0.6	99.7
III	41.9	11.7	2.5	14.3	11.2	11.5	2.7	0.7	0.8	2.6	99.9
IV	43.8	4.4	3.8	33.4	0.8	4.6	8.1	0.1	...	1.5	100.5
V	55.6	15.1	3.1	6.8	7.8	2.4	9.3	...	...	0.5	100.6

* XyO = small quantities of minor components.

I, Tremolite, Richville, Gouverneur, New York; II, Actinolite Greiner, Tyrol; III, Hornblende, Edenville, Orange County, New York: IV, Arfvedsonite, Kangerdluarsuk, Greenland; V, Glaucophane, Island of Syra, Greece.

Blowpipe and Chemical Characters. Tremolite, actinolite and common hornblende melt quietly or with little intumescence before the blowpipe, fusing rather easily at 4. The color of the bead depends on the amount of iron, tremolite nearly colorless, actinolite green or brown; common hornblende dark and shining. Common hornblende sometimes colors the flame yellow, indicating soda. Arfvedsonite fuses easily (3.5), colors the flame strong, persistent yellow, intumesces decidedly (difference from aegirite) and yields a black, shining, magnetic bead. The amphiboles are only slightly attacked by the ordinary acids, those rich in iron more than those without.

Alteration. The amphiboles have methods of alteration similar to those of the pyroxenes. Under the action of various agencies they may be changed into serpentine or into chlorite or into both, accompanied by the formation of carbonates, sometimes of epidote and also quartz. Under the continued action of weathering they may break down further in limonite, carbonates and quartz. Thus on much weathered rock surfaces only rusty-looking holes and spots may be left to show their former presence.

Occurrence. Amphiboles are common and widely distributed minerals playing an important rôle in igneous rocks and especially in the metamorphic ones. The presence of water, hydroxyl and fluorine in them shows that they are not formed by simple reactions like the pyroxenes but require the presence of mineralizing vapors; they are in some sense pneumatolytic minerals. Thus they cannot be artificially formed by allowing simple dry fusions containing their constituent silica and metallic oxides to cool and crystallize; pyroxenes are produced instead of them. And if hornblendes are fused and the melt allowed to crystallize we obtain pyroxenes, iron ore, etc., in their place; this is because the necessary water and fluorine have escaped.

Tremolite is chiefly found in the impure crystalline limestones and dolomites in the older schistose metamorphic rocks and in contact zones. In such occurrences it not infrequently has an extraordinarily fine fibrous structure and is capable of being split into long, flexible fibers of great fineness and strength, forming the greater part of what is known as *asbestus*. Sometimes actinolite and other hornblendes are found in this asbestus form. Some so-called asbestus is really a fibrous variety of serpentine.

Actinolite has its true home in the crystalline schists; it is the characteristic light green to bright green amphibole of many hornblende-schists and greenstones: in many of these cases it is secondary after original pyroxene of former gabbro and trap rocks as described under uralite.

Common *hornblende* occurs both in igneous and metamorphic rocks. It is found in granites, common syenites, and in the doleritic types; is in diorite and some varieties of peridotite. It may also be often observed in the phenocrysts of felsitic intrusive porphyries and lavas. In dark traps and basalt lavas it is rare. In the metamorphic rocks it is found in gneisses and is the prominent mineral of the hornblende schists.

Arfvedsonite occurs in nephelite syenites and in rare porphyries.

Uralite is a fibrous or fine needle-like, columnar hornblende, secondary after pyroxene and as mentioned under that mineral produced from it by metamorphic processes. Instances have been found where the outward crystal form of the pyroxene is retained but the substance composing it is this hornblende in parallel bundles of needle-like prisms. Generally it is in aggregates, which may be very fine and felt-like, lying in the plane of schistosity. It is especially apt to occur when basic, pyroxenic, igneous rocks have been subjected to dynamic changes in the earth's crust attended with squeezing and shearing. It varies in composition from actinolite to common hornblende, depending on the kind of pyroxene from which it was derived. It is clear that it cannot be a simple rearrangement of the pyroxene molecule since the latter has twice as much lime as the hornblende and is lacking in the necessary water or fluorine. Lime is separated out in the process to form a carbonate (calcite) or some other mineral and the presence of water, containing often other substances in solution, is a necessary aid to the dynamic processes of pressure and shearing which set up chemical activity and the reactions which produce this mineral.

In this connection the reader should consult what is said under metamorphism and the hornblende-schists.

Determination. Amphibole may be confused in megascopic work with pyroxene, tourmaline and epidote. To distinguish it from the last two use may be made of the various physical properties mentioned under the determination of pyroxene; the good cleavage separates it at once from tourmaline. The distinction from pyroxene is much more difficult, owing to the fact that these two minerals have similar chemical compositions and physical properties. The following points will be found of service in this connection. If the mineral appears in tolerably distinct crystals the form should be carefully studied, especially the outline of the section of the prism which can often be observed on a fractured surface of the rock and comparison made with Figs. 23 and 28.

In case the crystal form is imperfect or wanting, if it is possible, the angle at which the cleavage surfaces meet should be carefully studied, as this is a fundamental character, the cleavage prism as already described being nearly square in pyroxene and much more oblique in amphibole. Further, the perfection of the cleavage in amphibole and the bright glittering surfaces it yields furnish indications not commonly seen in pyroxene whose cleavage is only fairly good. Amphibole also is apt to occur in needles or long bladed prisms; pyroxene is commonly in short prismoids or grains. Before the blowpipe amphibole, on account of the combined water (hydroxyl), is more apt to intumesce than pyroxene (arfvedsonite from aegirite) but this cannot be relied on as a general definite test. If fluorine is obtained by a qualitative test this is also indicative of amphibole, but many do not contain this element and it is not a method which is ordinarily in one's power to make. Finally, in many cases, especially in fine grained igneous rocks, it is impossible by purely megascopic means to tell if the dark ferromagnesian mineral present is hornblende or pyroxene or, as often happens, a mixture of both. Only in a thin section under the microscope can this be certainly determined. This is a limitation which the megascopic method for the study and determination of rocks and rock-minerals imposes.

OLIVINE.

Form. Olivine crystallizes in the orthorhombic system; the crystals are rather complex as illustrated by a common form shown in Fig. 29. The form is not, however, a matter of importance, as the mineral very rarely shows well developed crystals in rocks but occurs in grains or small formless masses composed of grains.

General Properties. There is a cleavage parallel to the face *b* but it is not a very perfect or noticeable property in rock grains. The fracture is conchoidal. The color is green, generally of a medium shade and varying from olive-green to a yellow-green; a bottle-green is very common. It is often transparent varying to translucent but becomes brown to dark red on oxidation of the iron and more or less opaque; this is frequently noticed in lavas which have been exposed to the action of steam. Luster vitreous; streak white to yellowish. Hardness 6.5–7.0. Specific gravity varies with the iron from 3.3–3.5.

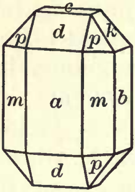


Fig. 29

Chemical Composition. Olivine is magnesium orthosilicate, Mg_2SiO_4, and ferrous orthosilicate, Fe_2SiO_4, which mingle isomorphously in all proportions. The nearly pure magnesium compound is called *forsterite,* the nearly pure iron compound *fayalite*; these occur in rocks but are rare. Much more common are variable mixtures of the two which make common olivine or chrysolite as it is often called. These variations may be seen in the following table of analyses.

	SiO_2	MgO	FeO	XyO*	Total.
I	41.8	56.2	1.1	0.7	99.8
II	39.9	49.2	10.5	...	99.6
III	37.2	39.7	22.5	...	99.4
IV	41.9	28.5	29.2	...	99.6
V	33.6	16.7	44.4	5.0	99.7
VI	30.1	...	68.2	1.5	99.8

* XyO = small quantities of other oxides, chiefly MnO.

I, Forsterite, Monte Somma, Italy; II, Olivine, Mt. Vesuvius, Italy; III, Olivine, Montarville, Canada; IV, Olivine, Hochbohl, Germany; V, Hortonolite, Monroe, Orange Co., N. Y.; VI, Fayalite, Rockport, Mass.

Blowpipe and Chemical Characters. Before the blowpipe nearly infusible; varieties very rich in iron fuse and yield magnetic globules — these are apt to turn red on heating. The powdered mineral dissolves in hydrochloric or nitric acid, yielding gelatinous silica on evaporation. The solution may be tested for iron and magnesium as directed under mineral tests.

Alteration. In one case this takes place through oxidation of the iron, the mineral turns reddish or brownish, and eventually a mass of limonite replaces it, accompanied with carbonates and some form of silica. The rusty iron product is the most noticeable feature of the process.

A most important mode of alteration is that by which the olivine becomes converted into serpentine. This appears to take place through the agents of weathering near the surface and deeper down through the action of heated waters. This is more fully discussed under the head of serpentine. Other substances such as carbonate of magnesia, iron ores, free silica, etc., are also liable to occur as by-products in the process. Other kinds of alteration of olivine are known but are of less importance in this connection.

Occurrence. Olivine is a quite characteristic mineral of igneous rocks, especially the ferromagnesian ones. It so rarely occurs in those composed chiefly of alkalic feldspars — in the granite-syenite rocks, feldspathic porphyries and felsite lavas — that for practical purposes it need not be sought in them. Anorthosite is the only feldspathic rock in which it may become of importance. Thus its true home is in the gabbros, peridotites and basaltic lavas. In the later it usually occurs in bottle-green grains; in the former it is sometimes colored dark by inclusions. It also forms masses of igneous rock known as dunite which consist almost wholly of olivine. Fine transparent crystals of olivine from basaltic lavas are frequently cut for gems, commonly called peridotes. The mineral is also often found in meteorites.

Olivine also occurs in metamorphic rocks, in crystalline limestones of dolomitic character and in other rocks found in such associations, composed of varying quantities of other magnesian (and lime) silicates, such as amphibole, pyroxene and talc. Its origin may be ascribed to a reaction between the magnesium carbonate of the dolomite and quartz sand or silica-bearing solutions.

$$2\,MgCO_3 + SiO_2 = Mg_2SiO_4 + 2\,CO_2$$

But in many such cases of its occurrence in the crystalline schists, mixed more or less with other silicate minerals, its presence is probably due to the fact that the masses containing it were originally of igneous origin, rather than metamorphosed sedimentary beds.

Determination. The appearance, associations and characters described above are usually sufficient to readily identify the mineral. It may be confused with greenish, more or less transparent grains of pyroxene, but the lack of pronounced cleavage, the superior hardness and easy gelatinization in acid enable one to distinguish it from that mineral.

GARNET.

Form. Garnets crystallize in the isometric system in the simple form of the rhombic dodecahedron shown in Fig. 30 or in the trapezohedron shown in Fig. 31. Sometimes, they show these forms well developed and are then excellent crystals, which may be more complicated by bevellings or truncations of the edges of the dodecahedron. Very commonly however the faces are not well developed and the mineral then appears as a spherical mass or grain.

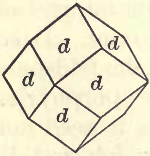


Fig. 30

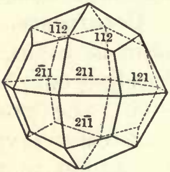


Fig. 31

Cleavage and Fracture. The cleavage is generally poor and not a prominent feature; sometimes a parting, in garnets occurring in sheared rocks, may be seen which suggests a lamellar structure. The fracture is uneven. The mineral is very brittle but some rocks composed largely of massive garnet are very tough.

Hardness and Specific Gravity. The hardness varies from 6.5–7.5; the specific gravity from 3.55 in grossularite to 4.2 in almandite, common garnet being about 4.0.

Color, Luster and Streak. The color depends upon the composition; *grossularite* is sometimes white but usually tinted pale tones of green, pink or yellow, sometimes yellowish or reddish-brown to brown; *pyrope* is deep red to black; *almandite* and most common garnet is deep red to brownish-red; *melanite* is black. Streak, light-colored, not important. The luster is glassy, sometimes rather resinous. The light-colored garnets are transparent to translucent, the darker ones translucent or opaque.

Chemical Composition. Garnets are orthosilicates of the general formula $\ddot{R}_3\dddot{R}_2(SiO_4)_3$, in which the radical $\ddot{R}$ may be calcium, magnesium, ferrous iron and other bivalent metals, while $\dddot{R}$ may be aluminum, ferric iron or chromium, trivalent elements. There is therefore opportunity for a number of combinations which are isomorphous. The most common ones which are of importance as rock minerals are *grossularite,* $Ca_3Al_2(SiO_4)_3$, *pyrope,* $Mg_3Al_2(SiO_4)_3$, *almandite,* $\ddot{F}e_3Al_2(SiO_4)_3$ and *andradite,* $Ca_3\dddot{F}e_2(SiO_4)_3$. These compounds, however, rarely, if ever, occur pure, generally there are variable amounts of the other molecules present and the mineral is named from the one predominating. *Common garnet* is chiefly *almandite* with more or less of the others present, especially the andradite molecule, and at times this may predominate. *Melanite,* the black garnet found in some rocks, is chiefly andradite. These facts are illustrated in the following analyses of typical specimens.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	XyO	Total.
I	39.8	22.1	1.1	...	0.7	36.3	...	100.0
II	40.4	19.7	4.0	6.9	20.8	5.8	2.6	100.2
III . . .	39.3	21.7	...	30.8	5.3	2.0	1.5	100.6
IV	35.9	19.2	4.9	29.5	3.7	2.4	4.8	100.4
V	35.7	0.1	30.0	1.2	0.1	32.3	0.9	100.3

I, Grossularite, Hull, Ontario. II, Pyrope, Krems, Bohemia, XyO = Cr_2O_3. III, Almandite, Fort Wrangell, Alaska, XyO = MnO. IV, Common Garnet (mostly almandite), Shimerville, Penn. XyO = MnO; V, Andradite, Sisersk. Ural Mts.

Blowpipe and Chemical Characters. The garnets fuse readily before the blowpipe and in the reducing flame those containing much iron become magnetic. After fusion and grinding of the bead to powder they dissolve in hydrochloric acid with gelatinization on boiling. They are slightly attacked by acids, andradite quite strongly. Give little or no water by heating in closed glass tube. Decomposed by fusion with sodium carbonate.

Alteration. Garnets change into other substances, commonly chlorite, serpentine, etc., and those containing iron oxides may alter into rusty spots of limonite and other products of weathering.

Occurrence. Common *garnet* is a widely distributed mineral as an accessory component of metamorphic and sometimes igneous rocks. Its most striking occurrence is in schists, especially in many mica-schists though it is also found in other kinds, in many hornblende-schists and in gneisses for example. It is apt to occur in the ferromagnesian igneous rocks which have been squeezed and sheared. It is sometimes seen in granite-pegmatites, rarely in granite itself, in occasional scattered crystals. It also occurs in the contact zone of igneous rocks where mixed beds containing clay, calcareous matter and limonite have been metamorphosed. *Pyrope,* which chiefly furnishes the garnet used as a jewel, is an accessory component of some peridotites and the serpentines derived from them. *Grossularite* is especially found in recrystallized limestone beds both in contact and regional metamorphism. *Melanite* occurs mostly in certain igneous rocks and is not an important megascopic mineral.

Determination. The crystal form of garnets, the appearance, color and hardness are generally sufficient to enable one to easily recognize them and in case of doubt the blowpipe tests will furnish sufficient confirmation.

EPIDOTE.

Form. Epidote crystallizes in the monoclinic system, the simplest form being that shown in Fig. 32, the crystals are apt to be more complex with other faces. Well-developed crystals usually occur only in druses in seams and cavities and the form is therefore not generally a character which can be of much use in megascopic rock determination. Commonly seen in bladed prisms extended in the direction of the edge *ac* and sometimes passing into slender, needle-like forms. Often in bundles or aggregates of prisms or needles. Terminations of prisms often rounded. Also occurs in spherical and angular grains and in aggregates of such grains.

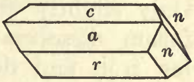


Fig. 32

General Properties. The *cleavage* is perfect parallel to *c*, parallel to *a* imperfect. Fracture uneven. Brittle. *Hardness* is 6–7. Specific gravity is 3.3–3.5. The *color* in general is green, usually of a peculiar yellowish, oily green; varying from pistache-green to olive, sometimes very dark green; rarely brownish. Luster vitreous. Streak whitish. Translucent to opaque.

Chemical Composition. Epidote is really the name of a group of complex silicates, salts of orthosilicic acid whose hydrogen atoms are replaced by calcium and by a set of isomorphous radicals composed of variable amounts of alumina, ferric iron and sometimes other oxides and of hydroxyl. Of these only common rock-making epidote is described in this section and its formula may be represented as being mixtures of $Ca_2(AlOH)Al_2(SiO_4)_3$ and $Ca_2(\dddot{Fe}OH)\dddot{Fe}_2(SiO_4)_3$. The composition may be seen in these two specimen analyses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	H_2O	XyO	Total.
I	37.8	22.6	14.0	0.9	23.3	2.1	. . .	100.7
II	37.0	25.8	10.0	1.3	21.9	3.0	1.0	100.0

I, Untersulzbach, Pinzgau. II, Macon Co., North Carolina, XyO = MnO and MgO = 0.5 each.

Blowpipe and Chemical Characters. Before the blowpipe epidote fuses easily with intumescence to a black slaggy mass. Intense heating in the closed glass tube causes the finely powdered mineral to give off water. Only slightly acted on by hydrochloric acid but after fusion dissolves and gelatinizes. Reacts with fluxes for iron and decomposes on fusion with sodium carbonate.

Occurrence. Epidote is characteristic as a product of alteration of other minerals. It appears through the weathering of igneous rocks which contain largely original lime, iron and alumina silicates and is then usually with chlorite. When igneous rocks of this character also suffer regional metamorphism epidote is apt to form. The occurrences in which it appears most notable from the megascopic view point are those in which mixed sedimentary beds containing calcareous matter, with sand clay and limonite (impure limestones) are subjected either to general or contact metamorphism. Then epidote is apt to be formed, usually in company with other silicates, but sometimes so extensively as to form masses which consist almost entirely of this mineral.

Determination. The peculiar yellow-green color, superior hardness, perfect cleavage in one direction only and the blowpipe characters described above generally suffice to distinguish epidote from hornblende, pyroxene and possibly tourmaline with which it might be confused. The hardness distinguishes it at once from some varieties of serpentine which resemble it in color. This may be confirmed by a chemical test showing the absence of magnesia as described in the section on mineral testing.

Zoisite. This is a mineral which has the same chemical composition as epidote and is closely related to it. It consists almost wholly of the lime-alumina molecule previously mentioned and contains little or no iron oxides. It is orthorhombic in crystallization but in the crystals seen in rocks this can generally only be told by optical methods: it occurs in aggregated blades or prisms, parallel or divergent or in grains and masses. Its color is usually gray of varying shades. From epidotes lacking in iron it can only be told by crystallographic investigations.

VESUVIANITE.

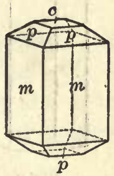


Fig. 33

Vesuvianite is a tetragonal mineral which generally crystallizes in short thick square prisms terminated by a pyramid commonly cut off by a basal plane as illustrated in Fig. 33. It also occurs in lumps or grains. The *cleavage* is poor, best parallel to the prism faces *m*; fracture uneven. The *color* generally varies from green to brown. The *luster* is vitreous. *Hardness*, 6.5. *Specific gravity* about 3.4. Subtransparent to subtranslucent. The *chemical composition* of vesuvianite is not exactly known; it is a silicate of calcium and aluminum containing hydroxyl and fluorine, but small amounts of ferric iron and magnesium are generally present. The formula has been written $H_4Ca_{12}(AlFe)_6Si_{10}O_{43}$ but this is probably not correct. Before the blowpipe it fuses readily with intumescence to a greenish or brownish glass, which gelatinizes with hydrochloric acid. The fresh mineral is slightly soluble in hydrochloric acid.

As a rock forming mineral vesuvianite characteristically occurs in limestones which have become crystalline through the contact action of igneous rocks and its formation is evidently conditioned by the pneumatolytic emanations of water and fluorine from the igneous magmas. In these occurrences it is commonly associated with garnet, pyroxene, tourmaline, chondrodite, and other contact minerals.

Vesuvianite may be confused with garnet, pyroxene, epidote or hornblende, but the study of its crystal form, its other physical characters and behavior before the blowpipe will generally serve to distinguish it from them.

STAUROLITE.

Form. Staurolite is orthorhombic in crystallization and usually in distinct crystals of the form shown in Fig. 34. They are often stout and thick, sometimes long and more slender but not strikingly so. The angle of the faces *m* on *m* is 50° 40′. They are terminated by flat bases *c*, though it often happens these cannot be seen in the rock. Staurolite is very apt to form compound twinned crystals as shown in Figs. 35, 36. From this fact its name is derived from the Greek, meaning a cross.

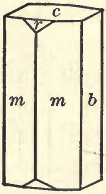


Fig. 34

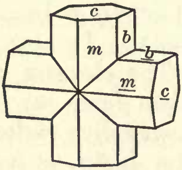


Fig. 35

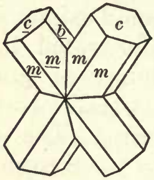


Fig. 36

Physical Properties. The mineral has a moderate but distinct cleavage parallel to the face *b;* the fracture is subconchoidal. The color varies from a dark reddish or yellowish brown to almost black, the light transmitted through thin splinters appears almost blood-red. The streak is white to gray. The hardness is 7-7.5, the specific gravity 3.75.

Chemical Composition. The formula is rather complex, $(AlO)_4(AlOH)\ddot{F}e(SiO_4)_2$, the alumina may be partly replaced by ferric iron and the ferrous iron by magnesia, as seen in the included analysis of a crystal from Franklin, North Carolina. The percentage of silica is very low;

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	H_2O	Total
27.91	52.92	6.87	7.80	3.28	1.59	=100.37

staurolite is one of the rock-forming silicates containing the least silica and this fact with the high alumina is significant of its place and mode of origin — in metamorphosed clay rocks.

Blowpipe and Chemical Characters. Staurolite is practically infusible before the blowpipe. It is almost insoluble in acids. It may be fused with carbonate of soda and the resulting fusion after solution in hydrochloric acid may be tested for alumina, iron and magnesia. It is easily recognized by its color, crystal form, hardness, method of twinning and mode of occurrence.

Occurrence. Staurolite occurs in the metamorphic rocks; it is a highly characteristic mineral of the crystalline schists. It is found in mica schists, in certain slates and sometimes in gneiss. Frequently it is associated with dark red garnets in these rocks.

ANDALUSITE.

Andalusite is orthorhombic in crystallization and is usually seen in rough prisms, nearly square in cross section. Sometimes the prisms are collected in radiated groups. The *cleavage* parallel to the prism is good — in other directions poor. *Fracture* uneven to subconchoidal. The normal *color* is white to pink or red to brown, but the mineral is very apt to contain impurities, especially particles of carbonaceous matter, which may color it dark or even black. Often these are arranged in a symmetrical manner in the crystal so that the cross section, when it is broken or cut, displays a definite pattern, such as a white cross in a black square. This may help to identify the mineral. It is usually *subtranslucent* in thin splinters. *Brittle. Hardness,* 7.5. *Specific gravity,* 3.2. *Streak,* whitish. The *chemical composition* is $Al_2SiO_5 = Al_2O_3 . SiO_2$. It is *insoluble* in acids but decomposed by fusion with carbonate of soda. Before the blowpipe it is *infusible;* after moistening with cobalt nitrate solution it turns a blue color upon intense ignition (as do also cyanite and some other alumina minerals).

Andalusite is a mineral characteristic of metamorphism, and especially of the contact zones of igneous rocks, such as granite. It is produced by the alteration of clay slates and shales as described on a later page. It occurs in mica schists and gneisses; sometimes though rarely it is found in granite.

CYANITE.

Cyanite usually occurs in long bladed crystals which rarely show distinct end faces, or in coarsely bladed columnar masses. It is triclinic. It has one very perfect cleavage (parallel to the face *a*) and another less so (parallel to *b*); the angle between these is about 74 degrees. The color is white to pure blue, sometimes the center of the blade is blue with white margins; rarely gray, green to black. Streak whitish. Transparent to translucent. Luster vitreous to pearly. Hardness varies in different directions from 5–7; least on face *a* (best cleavage) greatest on face *b* (second cleavage). Specific gravity, 3.56–3.67. Chemical composition, Al_2SiO_5, and other chemical and blowpipe properties similar to those of andalusite, mentioned above.

Cyanite is a mineral characteristically developed in regions subjected to intense regional metamorphism. It occurs in gneisses and in mica schists. In the latter case the mica is sometimes muscovite and sometimes the soda-bearing variety, paragonite. It is often associated with garnet, sometimes with staurolite or corundum. It alters to talc and steatite.

Cyanite is easily distinguished from other minerals, especially andalusite which has the same chemical composition by its form, color, variable hardness, specific gravity and other properties.

Sillimanite. With andalusite and cyanite may be mentioned sillimanite, a mineral which has a chemical composition identical with them, but which is separated mineralogically because it has a different crystal form as shown by its angles. Its chief importance is microscopical, but it may sometimes be seen with the eye or lens, mostly in gneisses or quartzites, as slender white or light-colored, four-sided prisms, or radiated aggregates of them forming brushes. Its blowpipe and other chemical characters are like those described for andalusite and cyanite.

TOURMALINE.

Tourmaline is a mineral of which there are a number of varieties based on the color, which in turn depends on the chemical composition. The chief ones are black, green, brown and red, but of these the black variety known also as *schorl* is the only one which is of importance in megascopic petrography.

Form. Tourmaline crystallizes in the rhombohedral division of the hexagonal system. The faces therefore are in threes or multiples of three. A simple form is shown in Fig. 37 and its appearance looking down upon the upper end in Fig. 39. It consists of the three-cornered prism *m* its edges bevelled by the prism faces *a* and terminated by the rhombohedron *r*. The crystals if well developed are apt to be more complicated than this, other faces being present and if both ends are perfect they have unlike faces. Though sometimes short and thick the crystals are commonly elongated prisms, often extremely long and thin. Very often also the faces *a* and *m* oscillate or repeat so that the prism is striated or channeled as shown in Fig. 38 and the outline and appearance from above is that seen in Fig. 40. This spherical triangle cross section is very characteristic of the prisms of rock-making tourmaline. It is rarely in formless grains or large shapeless masses. The slender prisms and needles are apt to be aggregated together into bundles, sheaves and radiate groups. The section of the latter in rocks furnishes the so-called "tourmaline suns."

Fig. 38

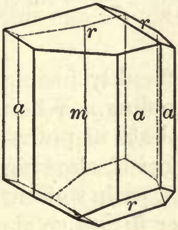


Fig. 37

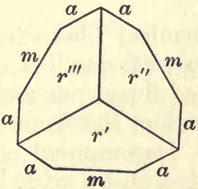


Fig. 39

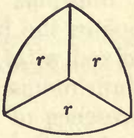


Fig. 40

General Properties. Tourmaline has no good cleavage and its fracture is rather conchoidal to uneven. It is brittle. The *color* is black, the luster glassy, sometimes dull, streak uncolored, not characteristic. Opaque. The *hardness* is 7–7.5, the specific gravity 3.1–3.2. It becomes electrified by friction.

Chemical Composition. Tourmaline is a very complex silicate of boron and aluminium with hydroxyl and sometimes fluorine and with magnesium, iron and sometimes alkali metals. It may be said to be a salt of an aluminium-borosilicic acid in which the hydrogens are replaced by iron, magnesium, alkalies and aluminium in varying amounts. This acid has been formulated as $H_9Al_3(BOH)_2Si_4O_{19}$ and in common black tourmaline the hydrogens are replaced mostly by iron or iron and magnesia as shown in the analyses here given.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	Na_2O	B_2O_3	H_2O	XyO	Total.
I. .	35.0	34.4	1.1	12.1	1.8	2.0	9.0	3.7	0.6	99.7
II .	35.6	25.3	0.4	8.2	11.1	1.5	10.1	3.3	4.3	99.8

I, Paris, Maine. II, Pierrepont, New York. XyO = small quantities of other oxides, etc.

Blowpipe and Chemical Characters. Difficultly fusible before the blowpipe with swelling and bubbling. When mixed with powdered fluor spar and bisulphate of potassium momentarily colors the flame a fine green, showing presence of boron. Decomposed on fusion with sodium carbonate. Not acted on by acids but after fusion gelatinizes in hydrochloric acid.

Occurrence. Tourmaline is not a common megascopic component of rocks, but it is of interest and importance because it is perhaps the most common and typical mineral which is produced in the pneumatolytic or fumarole stage of igneous rock formation as described in another place. This is shown by the boron, hydroxyl and fluorine which it contains. Thus it is one of the most common and characteristic accessory minerals found in the pegmatite dikes associated with intrusions of granites; its presence in granite indicates, as a rule, nearness to the contact and in the rocks which have suffered contact metamorphism it is very liable to appear. In this way it is not infrequently found associated with certain ore deposits. It appears at times also in gneisses, in schists and in crystalline limestones of the metamorphic rocks and its occurrence in these cases indicates that the metamorphism has been induced in part by the contact action of igneous masses giving off water vapors and other volatile substances. The beautiful red and green transparent tourmalines which are valued as gem material occur in pegmatite dikes of granite, often associated with the common black variety. The red is usually found with lepidolite — the lithia mica.

Determination. The black color, crystalline form, and mode of occurrence of common tourmaline are usually sufficient to identify it. From black hornblende it is easily distinguished by its lack of good cleavage, superior hardness and the shape of the cross section of the prism and this can be made certain by the blowpipe test for boron.

TOPAZ.

Topaz crystallizes in the orthorhombic system and the *form* in which it is generally seen is in pointed prisms, as illustrated in Fig. 41. There is a very perfect *cleavage* parallel to the base c, at right angles to the prism: the *fracture* is uneven. The mineral is very hard = 8, and brittle. The specific gravity is about 3.5. In color it is, while generally transparent, often colorless, sometimes yellow to brown-yellow, sometimes white and translucent. The *luster* is vitreous. The *chemical composition* as established by Penfield is $(AlF_2)SiO_4$ in which the fluorine may be replaced in part by hydroxyl (—OH). Before the blowpipe it is infusible. If fused in a closed tube with

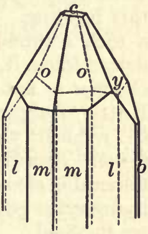


Fig. 41

previously fused and powdered phosphorus salt hydrofluoric acid will be given off which etches the glass and deposits a ring of silica on the colder upper walls of the tube. If the pulverized mineral be moistened with cobalt nitrate solution and intensely heated before the blowpipe on charcoal it assumes a fine blue color showing presence of alumina.

Topaz, while not a common or important rock-forming mineral, is a very interesting one as it is particularly characteristic of the pneumatolytic stage in the formation of igneous rocks.

Thus it is found in crystals in the miarolitic cavities of granites where the vapors have collected and in the same way in felsite lavas (especially in rhyolite). It is also found in pegmatite dikes and in the cracks and crevices of the surrounding rocks which have served as channel ways for the escape of gases as explained under the description of pegmatite dikes and of contact metamorphism. It is apt to be associated in these occurrences with quartz, mica, tourmaline and sometimes with cassiterite, tin ore.

The form, color, cleavage and great hardness of topaz, together with its mode of occurrence, serve to readily distinguish it from other minerals and the determination may be confirmed by the chemical tests mentioned above.

CHONDRODITE.

Chondrodite is really one of a small group of minerals — chondrodite, humite, clinohumite, etc. — which are so closely allied in all of their general properties that for practical megascopic rock work they are indistinguishable and may all be comprised under this heading. While the mineral is monoclinic it rarely shows, as a rock component, any definite crystal form which is of value in determining it, but appears as embedded grains and lumps. The *cleavage* is not marked but is sometimes distinct in one direction. Brittle; fracture subconchoidal. The *color* is yellow, honey yellow to reddish yellow, to brown red. *Luster* vitreous. *Hardness* 6–6.5. *Specific gravity* 3.1–3.2. In *chemical composition* the mineral is closely allied to olivine but differs in containing fluorine or hydroxyl or both, as may be seen from the following formulas deduced by Penfield.

Olivine = Mg_2SiO_4.
Chondrodite = $Mg_3[Mg(F,OH)]_2(SiO_4)_2$.
Humite = $Mg_5[Mg(F,OH)]_2(SiO_4)_3$.
Clinohumite = $Mg_7[Mg(F,OH)]_2(SiO_4)_4$.

As in olivine part of the magnesium is usually replaced by some ferrous iron. The powdered mineral is slowly dissolved by hydrochloric acid, yielding gelatinous silica. The solution evaporated to dryness, then moistened with acid and taken up in water, after the silica is filtered off, yields tests for iron with excess of ammonia and after its separation by filtering, for magnesia with sodium phosphate solution. From olivine it may be distinguished by a test for fluorine as described under topaz. Before the blowpipe it is nearly infusible.

The characteristic mode of occurrence of chondrodite is in limestone, especially dolomite, which has been subjected to contact action of igneous rocks. In them it forms yellowish or reddish embedded grains or lumps usually associated with other contact minerals such as pyroxene, vesuvianite, magnetite, spinel, phlogopite, etc. The presence of the hydroxyl and fluorine shows its derivation by pneumatolytic processes.

The appearance, color, mode of occurrence and associations are usually sufficient to identify the mineral, and these may be confirmed by the chemical tests mentioned.

b. Oxides, etc.

The list of important rock-making oxides includes first, silica, SiO_2 and then corundum, Al_2O_3. Then come the oxides of iron which are of importance as nearly constant accessory minerals in rocks and therefore have a wide distribution. For this reason two other minerals not oxides, pyrite, the sulphide of iron, and apatite, the phosphate of lime, are also here included. Limonite, the hydrated oxide of iron, which is always secondary, is placed with the other iron ores for the sake of convenience.

QUARTZ.

Form. Quartz crystallizes in the hexagonal system, the ordinary form being a hexagonal prism terminated by a six-sided pyramid. This form, which is the common one for the crystals of veins and is illustrated in Fig. 42, is not often seen in the quartzes of rocks, except in igneous rocks which possess miarolitic or drusy cavities; into them the rock-making quartzes project with free ends which show crystal form. The large crystals seen in pegmatite veins and which sometimes attain huge dimensions are only a manifestation of the same thing on a larger scale, as explained under the pegmatite formation of igneous rocks.

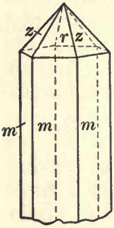


Fig. 42

In porphyries where quartz may have crystallized free as phenocrysts it tends to take the form shown in Fig. 43; the two pyramids are present and the prism is very short or even wanting. Since the crystals are usually poorly developed, with rough faces, they appear as spherical objects, like shot or peas, embedded in the rock, with round cross sections where broken across on a fracture face. In general, quartz has no definite form in rocks, especially in igneous ones like granite, where, being usually the last substance to crystallize, its shape is conditioned by the other minerals which have already formed. In granites, therefore, it commonly appears in small shapeless lumps and masses, but in some of the fine-textured varieties the quartz tends to appear in granules like those composing lump sugar. In pegmatite dikes it appears on fracture surfaces in curious script-like figures intergrown with feldspar, forming the substance known as graphic granite.

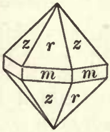


Fig. 43

Cleavage and Fracture. The cleavage of quartz is so poor that for practical petrographic purposes it may be regarded as not possessing any. It has commonly a good conchoidal fracture which is a great help in distinguishing it in granitic rocks but in some massive forms it is uneven and splintery. The mineral is brittle to tough.

Color and Luster. Rock-making quartz varies in color from white through shades of gray and dark smoky gray or brown to black. The gray and smoky tones are most common in igneous rocks and the white color in the sedimentary and metamorphic ones but there is no absolute rule about this. The black color is rare and mostly confined to igneous rocks; sometimes in them it has a strong bluish tone. The colorless, limpid quartz, so characteristic of the crystals found in veins and geodes and deposited by solution, is rare as a rock-making component but sometimes occurs as in some very fresh lavas. The mineral may also at times possess an exotic color given it by some substance acting as a pigment; thus it may be red from included ferric oxide dust or green from scales of chlorite, and in the sedimentary and metamorphic rocks, such as quartzite, it may be very dark from included organic matter or charcoal-like substance.

The luster varies from glassy to oily or greasy. The *streak* is white or very pale colored and not a prominent character. *Hardness*, 7. Scratches feldspar and glass but is not touched by the knife. *Specific Gravity* = 2.66.

Composition. Pure silica, SiO_2. This is the composition of the crystallized common rock-making quartz, but certain massive varieties of silica, which are not crystallized or not apparently so, and are of common occurrence and sometimes take part in forming rocks, such as jasper, opal, chert, etc., contain in addition more or less combined water, while impurities like clay, oxides of iron, etc., are usually present and give them distinctive colors.

Blowpipe and Chemical Characters. Quartz is infusible before the blowpipe — varieties dark from organic matter whiten but do not fuse. Fused with carbonate of soda, it dissolves with effervescence of CO_2 gas. In the sodium metaphosphate bead a fragment floats without dissolving. It is insoluble in acids except hydrofluoric, HF.

Occurrence. Quartz is one of the commonest of all minerals, and is universally distributed, occurring in igneous, sedimentary and metamorphic rocks alike. Not only does it form rocks in company with other minerals, chiefly feldspar, but in pure sandstones and quartzites it may be the only one present in the rock-mass. It is indeed so common that, with the exception of the limestones and marbles and dark heavy igneous rocks like dolerite and basalt, its presence in rocks should at least always be suspected.

Determination. The hardness of quartz, its lack of cleavage, its conchoidal fracture and generally greasy luster are characters which help to distinguish it, especially from the feldspars with which it is so often associated. The gray and smoky color it often has in granites and other igneous rocks helps in the same way. It may be confused with nephelite but this mineral is readily soluble in acids with gelatinization and moreover is very rare. These characters, with the blowpipe and chemical ones mentioned above, will readily confirm its determination.

Opal, Jasper, Flint, Chalcedony, etc. Silica, in addition to forming the crystallized anhydrous mineral quartz, occurs in non-crystalline, amorphous masses which contain varying amounts of water. Accordingly as the color, structure and other properties vary, a great number of different varieties are produced which have received particular names. For a description of them the larger manuals of mineralogy should be consulted. They seem to have been formed, in large part at least, by the evaporation of liquids containing soluble silica, which on the drying down has been deposited in an amorphous, more or less hydrated condition instead of as crystalline quartz. Sometimes they are a mixture of quartz particles or fibers mixed with amorphous material. This form of silica is illustrated by the gelatinous product obtained when a silicate like nephelite is dissolved in an acid and the resulting solution evaporated. It is also formed in nature as a secretion from water by various living organisms.

Amorphous silica is not a rock component of any megascopic importance in igneous or metamorphic rocks, but in the sedimentary ones it forms accompanying masses and sometimes beds which, although not of wide general importance, may be of considerable local interest and value. These are further noticed in their appropriate places. It may also act as a cementing substance of the grains of some rocks.

CORUNDUM.

Form. The crystallization is hexagonal and the form assumed is either a thick six-sided prism often swelling out in the middle into barrel-like shape or in thinner six-sided tables; also commonly in grains or shapeless lumps. The thick and barrel forms are most common when it occurs in massive rocks like the syenites, and they are associated with the grains and lumps. Sometimes on parting faces a multiple twinning resembling that illustrated as occurring on feldspars may be observed, produced however by another method.

Cleavage. Corundum does not have a good cleavage but possesses a parting that appears like perfect cleavage parallel to the base of the prism and also in three other directions at an angle to it (parallel to the unit rhombohedron). In large pieces these partings or pseudocleavages may appear nearly at right angles and the mineral has a laminated structure.

Color, Luster, and Hardness. Rock-making corundum is usually dark gray to bluish gray or smoky. It is very rarely blue forming the variety sapphire, while the red variety or ruby is excessively rare. The luster is adamantine to vitreous, sometimes dull and greasy in rock grains. Translucent to opaque. It is the hardest of rock minerals = 9. Brittle, though sometimes very tough. Specific Gravity = 4.

Blowpipe and Chemical Characters. Before the blowpipe it is infusible. The powder moistened with cobalt solution and intensely ignited turns bright blue showing alumina. It is insoluble in acids. Its composition is pure alumina, Al_2O_3. By the action of weathering and alteration it is apt to change into muscovite.

Occurrence. In recent years corundum has been recognized as an important primary mineral in the igneous rocks of a number of regions, in syenites in Canada, Montana and India, in peridotites in North and South Carolina and Alabama, and in other igneous rocks in the Urals and in California. An unrecorded occurrence is in syenite in Orange County, New York State. Many more such will doubtless be discovered. The variety sapphire has been found in basaltic rocks in Montana, the Rhine district and elsewhere. Corundum also occurs in the contact zone of igneous rocks. In these cases it is usually in thin tabular crystals. It also occurs in metamorphic rocks, sometimes in thick beds of the variety called emery. Probably in many of these occurrences it antedates the period of metamorphism and is of igneous origin.

Determination. The crystal form, when present, and color indicate the presence of this mineral which is readily confirmed by a test of its hardness since it cannot be scratched by another of the rock minerals. These tests may be confirmed by the other described properties.

THE IRON ORES.

The term ore is commonly applied to the oxides, sulphides and carbonates of the heavy metals as the sources from which they are obtained in commercial quantities. Of these minerals the only ones, which by reason of their wide distribution and common occurrence as components of rocks, may be considered of general importance from the petrological standpoint are the oxides and sulphides of iron. Even these play only a subordinate rôle in rock-making and are considered as accessory minerals, except in certain cases where they have been concentrated by geologic processes into considerable masses. They are considered accessory because, in one form or another, they are found scattered in small quantities through most rocks and in each of the three great classes of rocks and do not therefore have the same importance and value in classification that those minerals, such as feldspars and pyroxenes have, which occur in large and varying amounts. They are mentioned here because they are the most common of accessory rock-minerals and are of importance in other ways as well. They include *magnetite*, *ilmenite*, *hematite*, *limonite* and *pyrite*. There are other oxides and sulphides of iron but they are relatively of small petrographic importance.

MAGNETITE.

Form. Magnetite crystallizes in the isometric system, most commonly in octohedrons, Fig. 44, sometimes in dodecahedrons, Fig. 45, sometimes in a combination of both, Fig. 46. It is sometimes seen in distinct crystals in rocks but usually is in small grains whose form cannot be made out and is sometimes in larger irregular masses.

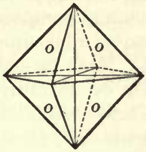


Fig. 44

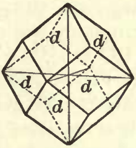


Fig. 45

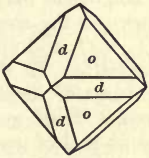


Fig. 46

General Properties. No distinct cleavage but sometimes a parting parallel to the octahedral faces resembling cleavage. Fracture, uneven. Brittle. Color, dark gray to iron-black; opaque; luster, metallic, fine to dull. Resembles often bits of iron or steel in the rocks. Streak, black. Magnetic. Hardness, 5.5–6.5. Specific gravity, 5.2. The chemical composition is $Fe_3O_4 = \ddot{F}eO \, . \, \dddot{F}e_2O_3$, or $FeO = 31.0$ per cent, $Fe_2O_3 = 69.0$. Difficultly fusible before the blowpipe and in the oxydizing flame becomes non-magnetic. Slowly soluble in hydrochloric acid.

Occurrence. Magnetite is one of the most widely distributed of all minerals. It is found in all kinds of igneous rocks, usually in small grains, but sometimes segregated into considerable masses. It occurs also in rocks produced by contact metamorphism and in the crystalline schists, sometimes in large bodies. It is uncommon in the unmetamorphosed sedimentary rocks. It is one of the most important ores of iron.

Determination. The appearance of magnetite in small dark metallic-looking particles is usually sufficient to distinguish it in the rocks, and this may be confirmed by a test of its hardness, streak and magnetism, together with the other properties described above. It is not liable to be confused with any other mineral except ilmenite.

SPINELS.

Magnetite may be regarded as the type of a group of minerals known as the spinels. They have the general chemical composition $\ddot{R}O\,.\,\dddot{R}_2O_3$ and crystallize in isometric octahedrons as illustrated in magnetite. In them the RO is either MgO, FeO, MnO or ZnO or mixtures of them; R_2O_3 is Fe_2O_3, Al_2O_3 or Cr_2O_3 or mixtures of them. True spinel is $MgAl_2O_4(MgO\,.\,Al_2O_3)$ and when transparent and of good color is sometimes cut as a gem. Hercynite is iron spinel, $FeAl_2O_4$, and chromite is $FeCr_2O_4$, more or less mixed with other spinel molecules. Depending on their composition the spinels have various colors, black, green, red and gray. They are extremely hard, 7–8, without good cleavage and are of high luster to pitchy. Some of the spinels are constituents of igneous rocks, especially of those low in silica and rich in iron and magnesia like peridotite and dunite; others are found in metamorphic rocks, especially those produced by contact metamorphism. In all cases they form only accessory and not important components of the rocks and, except in some contact rocks, are rarely found in crystals sufficiently large to make them of megascopic importance.

ILMENITE.

General Properties. Ilmenite crystallizes in the hexagonal system like hematite, but it is so rarely seen in good megascopic crystals in rocks that its crystal form is not a matter of importance. It usually occurs in embedded grains and masses, sometimes in plates of irregular to hexagonal outline. No cleavage; fracture, conchoidal; brittle. Color, iron-black, sometimes with faint reddish to brownish tinge; luster, submetallic; streak, black to brownish-red. Opaque. Hardness, 5–6. Specific gravity, 4.5–5. Composition, $FeTiO_3 = FeO\,.\,TiO_2$. $FeO = 47.3$, $TiO_2 = 52.7$. Is not generally pure, but more or less mixed with hematite, Fe_2O_3, with which it is isomorphous. Before the blowpipe very difficultly fusible; in the reducing flame becomes magnetic. After fusion with carbonate of soda can be dissolved in hydrochloric acid and the solution boiled with tin becomes violet showing titanium. Fresh mineral difficultly soluble in acids; decomposed by fusion with bisulphate of potash. The solutions give reaction for iron with potassium ferricyanide. The test for titanium is the safest method to determine the mineral.

Occurrence. Ilmenite or titanic iron ore, as it is often called, is a widely spread mineral occurring as a common accessory mineral in igneous rocks in the same manner as magnetite which it often accompanies. In the same way it is found in gneisses and schists. Unless the embedded grains are of such size that they can be safely tested it cannot usually be discriminated from that mineral by simple inspection. The most important megascopic occurrences are in the coarser grained gabbros and anorthosites where the mineral is very common and is indeed not infrequently segregated in places into such large beds and masses that it would be a useful ore of iron if some method of profitably smelting it could be discovered.

HEMATITE.

Form. Hematite crystallizes in the rhombohedral division of the hexagonal system but is so rarely in distinct well-formed crystals of observable size as a rock constituent that this is not a matter of practical importance.

It occurs as a rock-mineral in three different forms: as *specular iron ore, micaceous hematite,* and as *common red hematite.*

In the first case it forms masses and plates, the latter sometimes hexagonal in outline. Its color is black to steel-gray with sometimes a faint reddish tone. It is opaque, has a metallic luster which is sometimes very fine or splendent so that it resembles polished steel or iron, at other times it is rather dull but metallic-looking. Fracture, subconchoidal; no cleavage.

As micaceous hematite it is in thin flakes which somewhat resemble mica; often they are so thin as to be translucent and then have a deep red color. The luster is submetallic to metallic, sometimes splendent like the specular form. The thin leaves are usually of ragged outlines but sometimes hexagonal.

Common red hematite does not appear crystallized. The mineral is massive, sometimes columnar or granular, often in stalactitic or mamillary forms and sometimes earthy. It is dull, without metallic luster, opaque and of a dark red color.

General Properties. The streak of hematite is of a red color, from bright Indian red to brownish red and furnishes the most convenient method of distinguishing it from magnetite and limonite. Before the blowpipe it is very difficultly fusible except in very fine splinters. After heating in the reducing flame magnetic. Dissolves slowly in hydrochloric acid and the solution gives reactions for iron.

The composition is Fe_2O_3, ferric oxide. The hardness varies from 5.5–6.5; specific gravity of the specular variety is 5.2.

Occurrence. Hematite is one of the most widely diffused of minerals. The specular variety is a common accessory component of feldspathic igneous rocks, such as granite. It is also found in the crystalline schists, often in thick beds and masses.

Micaceous hematite occurs in the crystalline schists in megascopic form, as in itabirite, and also in minute microscopic scales it is the red coloring matter found in igneous and metamorphic rocks. The red color of many potash feldspars is due to it and so is that of many slates.

Common red hematite is found in sedimentary and metamorphic rocks in beds and masses, often of great size and forming one of the most valuable ores of iron. It is the interstitial cement of many stratified rocks, such as red sandstones, and as a red pigment in the form of powder it is everywhere distributed in all classes of rocks and in soils, though possibly in some cases it may be replaced by turgite (hydrohematite), $2Fe_2O_3.H_2O$, which often closely resembles it. Earthy red hematite, usually more or less mixed with clay, is called red ocher.

LIMONITE.

Form. Limonite does not crystallize, but occurs in earthy formless masses in the rocks, and when found in considerable deposits very frequently exhibits compact stalactitic or mammillary shapes which have a fibrous or radiating structure and are sometimes concretionary; sometimes in earthy beds or deposits.

General Properties. No cleavage. Luster of compact varieties often silky to sub-metallic, but generally dull and earthy. Color, various shades of brown from very dark to brownish yellow. The surface of the compact stalactitic or mammillary forms often has a varnish-like skin. Opaque. Streak, yellow-brown. The hardness of the compact mineral varies from 5–5.5 and the specific gravity from 3.6–4.0. The composition is $2\ Fe_2O_3.3\ H_2O$ or $Fe_2(OH)_6.Fe_2O_3$, partly dehydrated ferric hydroxide. $Fe = 59.8$; $O = 25.7$; $H_2O = 14.5 = 100$. Difficultly fusible before the blowpipe; becomes magnetic in the reducing flame. Heated in closed glass tube gives off water. Slowly soluble in hydrochloric acid, the solution giving reactions for iron. The yellow streak is the most convenient means of distinction from hematite.

Occurrence. Limonite occurs in several different ways. In all cases it is strictly a secondary substance formed at the expense of previously existing minerals, by the various agencies of weathering and alteration. In igneous and metamorphic rocks it is frequently seen as small, earthy, yellowish to brownish masses which represent the decay of some previous iron-bearing mineral, such as pyrite, hornblende, etc. Accumulated in beds, as explained under sedimentary rocks, it frequently has the compact form with stalactitic and mamillary or concretionary structure.

As bog iron ore it is loose, porous and earthy. Mixed with more or less clay it forms yellow ocher and is the yellow pigment of many soils and sedimentary rocks.

PYRITE.

Form. Pyrite almost invariably occurs in crystals in the rocks, very seldom in grains and masses. It crystallizes in the isometric system. It is frequently seen in cubes or in the twelve-sided form seen in Fig. 47 and called the pyritohedron because this mineral so commonly shows it. Combinations of the two are also very common as shown in Fig. 48. Very often the cubic faces are striated by fine lines as seen in Fig. 50 produced by oscillating or repeating combinations of the pyritohedron on the cube faces. The octahedron is less frequent and is apt to be modified by the pyritohedron combining with it as in Fig. 49. Other more complex forms also occur.

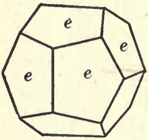


Fig. 47

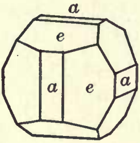


Fig. 48

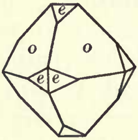


Fig. 49

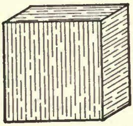


Fig. 50

General Properties. No good cleavage; fracture, conchoidal to uneven. Color, brass yellow; luster, metallic, splendent, duller when tarnished. Opaque. Streak, greenish to brownish black. Hardness, 6–6.5; specific gravity, 5.0. Composition, FeS_2; iron = 46.6, sulphur = 53.4 = 100. Easily fusible before the blowpipe, burning and giving off sulphur dioxide gas, and leaving a magnetic globule. In the closed glass tube on heating gives a sublimate of sulphur and leaves a magnetic residue. Insoluble in hydrochloric but decomposes in boiling nitric acid with separation of sulphur.

The color and crystallization are usually sufficient to at once identify pyrite and distinguish from other rock minerals. From pyrrhotite, $Fe_{11}S_{12}$, and chalcopyrite, $FeCuS_2$, other sulphides of iron which occasionally may be seen in rocks, the test of hardness discriminates it from chalcopyrite (3.5) which can be readily scratched with the knife and gives reactions for copper; pyrrhotite has a bronze color, is also scratched by the knife and gives little or no sulphur in the closed tube.

Occurrence. Pyrite is a mineral which has many different modes of origin and in consequence is found in all kinds of rocks as a scattered accessory component, usually in small distinct crystals, less commonly aggregated. The largest masses are found in ore deposits, chiefly formed in contact zones of igneous rocks through the action of mineralizing solutions. In igneous rocks it appears as a primary product of crystallization from the molten magma. In sedimentary rocks it is frequently found replacing fossils, and its occurrence must be due to reactions between the sulphur of albuminous materials of organic life and the iron in the rocks. It is common in coal seams.

APATITE.

Apatite crystallizes in hexagonal prisms either rounded at the ends or capped by a six-sided pyramid. It is scratched by the knife, has a vitreous luster and is white to green or brown in color. No good cleavage. Brittle. Transparent in small crystals to opaque in large. Very difficultly fusible. Dissolves in nitric acid and ammonium molybdate solution added to a few drops of the nitric acid solution gives a bright yellow precipitate showing the presence of phosphorus. Composition $(CaF)Ca_4(PO_4)_3$; phosphate of lime with fluorine; the fluorine is often replaced wholly or in part by chlorine. Apatite is found in large, sometimes huge, crystals in pegmatite dikes and in metamorphosed limestones in the crystalline schists: these may be said to be the chief megascopic modes of occurrence. In these, however, it cannot be said that its function as a rock-mineral is of any wide or general importance. In addition to this it occurs in minute microscopic crystals, which can seldom be detected with the eye or lens, in all kinds of igneous rocks and in many metamorphic ones. Microscopical study of the thin sections of such rocks has shown that in this form the mineral has a nearly universal distribution as a constant accessory component. Although the relative proportion of the mineral is small, rarely rising above two or three per cent of the rock, its presence is a matter of great importance, since by it the phosphorus, so necessary to vegetable and animal life (in bones, etc.), is furnished to the soil which is formed when the rocks decay and break down under the action of the various agents of weathering.

SEC. 2. *Hydrous Silicates.*

The minerals of this group are of purely secondary origin; they are formed from previously existent ones by the agencies of weathering, water containing carbon dioxide or vegetable acids and by heated water or its vapors circulating in already solid, existent rocks. Thus they do not play any important part in fresh unchanged igneous rocks; only as these alter do they become of importance in them; their true home is in the metamorphic and sedimentary ones, which at times are made up wholly of these minerals.

The important ones to be considered in this section are *kaolin, chlorite, serpentine, talc* and *zeolites.* Some micas would also naturally be considered here and among secondary minerals also limonite, but, for reasons previously stated, these have been treated in the foregoing section.

KAOLIN—CLAY.

Under the heading of clay are included certain hydrous silicates of alumina having well-known physical properties by which they are distinguished. By far the most common and important of these is kaolin which may be taken as a type of the group, and the only one which need be considered here in detail.

General Properties. Kaolin crystallizes in the monoclinic system forming thin plates or scales often with hexagonal outlines which are flexible and recall mica but are inelastic; these are generally so minute and aggregated together that the crystal form is not a matter of importance in megascopic determination of the substance. Usually in masses, either compact, friable or mealy. Color white, often tinted yellow, brown or gray. Neither the hardness (2–2.5) nor the specific gravity (2.6) can be used for practical tests. On rubbing between the fingers kaolin has a smooth, unctuous, greasy feel, which helps to distinguish it from fine aggregates of some other minerals occurring in nature: thus its presence in soils can usually be told by rubbing out the fine, gritty particles of quartz, feldspar, etc., and observing if there is a smooth, unctuous residue of clay.

It is infusible before the blowpipe, but moistened with cobalt nitrate and ignited turns blue showing presence of alumina. Heated in the closed glass tube it yields water. Insoluble in hydrochloric acid. In the phosphorus bead before the blowpipe, undissolved silica is left; this test helps to distinguish it from *bauxite,* a hydrated oxide of aluminum ($Al_2O(OH)_4$) which very much resembles it and sometimes occurs in considerable deposits. Bauxite dissolves in the phosphorus bead completely. The chemical composition of kaolin is $H_4Al_2Si_2O_9$· a combination of $Al_2O_3 \,.\, 2\,SiO_2 \,.\, 2\,H_2O$.

Occurrence. Kaolin is always a secondary mineral formed by the alteration or weathering of previously existent aluminous silicates and chiefly feldspar. The reaction by which it is formed from alkalic feldspar is one of the most important in nature, for by it soil is chiefly made and the alkali necessary for plant food liberated and converted into soluble form. It is expressed as follows:

$$\begin{array}{lllllll}
\text{Orthoclase} & + \text{ Water} & + \text{ Carb. diox.} & = & \text{Kaolin} & + \text{ Potas. Carb.} & + \text{ Quartz.} \\
2\,KAlSi_3O_8 & + 2\,H_2O & + \quad CO_2 & = & H_4Al_2Si_2O_9 & + \quad K_2CO_3 & + 4\,SiO_2.
\end{array}$$

This process and reaction have been already described under feldspars. The feldspathoids also yield kaolin and the process could be expressed as follows:

$$\begin{array}{llllll}
\text{Nephelite} & + \text{ Water} & + \text{ Carb. diox.} & = & \text{Kaolin} & + \text{ Sodium Carb.} \\
2\,NaAlSiO_4 & + 2\,H_2O & + \quad CO_2 & = & H_4Al_2Si_2O_9 & + \quad Na_2CO_3.
\end{array}$$

They are more apt however to first change into muscovite or zeolites and these ultimately to clay.

From what has been said it is clear that feldspathic rocks furnish kaolin, and every stage of the change may be observed in nature as described more completely in the chapter dealing with the origin of sedimentary rocks and soils. Thus kaolin occurs intimately mixed with the feldspar substance of such rocks as are undergoing this change; it is found occasionally in quite extensive deposits where such rocks have been completely altered in place, and the products of decay yet remain where they have been formed, and lastly it occurs in extensive beds in the sedimentary formations. Since the particles of kaolin are very minute, light and flat they remain much longer in suspension than the other products of land waste, and thus in erosive and sedimentary processes there is a constant tendency to separate them from the other particles. We find beds of clay with every degree of admixture with sand, etc., that pass into sandstones and other rocks but not infrequently they are of a high degree of purity.

CHLORITES.

The chlorites are an ill-defined group of hydrous silicates so named on account of their green color (Greek χλωρός, green), which are always secondary and formed at the expense of previously existing silicate minerals which contain aluminum, iron and magnesia. Outwardly they resemble the micas, but unlike them their folia are soft and inelastic. They are hydrous silicates of aluminium with ferrous iron and magnesium. They have certain common properties by which they may generally be easily recognized as a group, but the identification of the different members is usually a difficult matter and for ordinary purposes of megascopic petrography of little importance. In the description which follows then it is these general group properties which are given, though these are based largely on the species clinochlore which is perhaps the most common and best known of the group.

Form. The chlorites are really monoclinic in crystallization, but, like the micas, when crystal form can be observed they are generally in six-sided plates and tablets. More commonly they occur in irregular leaves and scales which are aggregated together into fine granular or coarse leafy massive forms or arranged into fan-like or rosette-like groups. The scales are sometimes flat; often bent or curled.

General Properties. Chlorite, like mica, has a highly perfect cleavage in one direction parallel to the flat base of the plates. The cleavage leaves are flexible and tough but unlike mica they are inelastic. Luster of cleavage face rather pearly. Color green, variable, usually a rather dark green. Usually translucent. Hardness, 2–2.5 soft, just scratched by the finger nail. Specific Gravity about 2.7. Streak pale green to white. The chemical composition of the chlorites is not definitely understood and seems to be complex: it may be illustrated by the formula assigned to clinochlore, $H_8(Mg\ddot{F}e)_5Al_2Si_3O_{18}$, which may be written $4\,H_2O\,.\,5\,(MgFe)O\,.\,Al_2O_3\,.\,3\,SiO_2$: Ferrous iron and magnesia are isomorphous. In kämmererite, a rare violet-red variety, part of the alumina is replaced by chromic oxide, Cr_2O_3. Before the blowpipe chlorites are infusible or very difficultly so; with the borax bead they react for iron. Heated in the closed glass tube they yield water. They are insoluble or difficultly so in hydrochloric acid but are decomposed in sulphuric acid. These reactions are those of the common kinds.

Occurrence. The chlorites are a widely spread group of minerals, and occur wherever previously existent rocks containing silicates composed of alumina, iron and magnesia, such as dark micas, amphibole, pyroxene and garnet, are being altered by geologic processes. To chlorite many igneous rocks owe their green color, the original ferro-magnesian silicates having been broken down by decay and changed more or less completely into this substance. They are apt to lose their original bright, clean appearance and hard clear-cut fracture and become dull green and more or less soft and even earthy. This change can also be often observed in the case of single embedded crystals of the above-mentioned minerals, which become soft, dull green masses.

Chlorite is also of common occurrence in the schistose rocks; in chlorite-schist it is the prominent component accompanied by other minerals; other schists often owe their green color to its presence, as in green slates for example. Thus in finely disseminated particles it is a common coloring matter.

SERPENTINE.

General Properties. Serpentine does not crystallize, and therefore has no crystal form of its own, but it is sometimes found in the crystal form of other minerals which have been altered to this substance. It is usually massive, sometimes finely granular or even slaty; sometimes fibrous, the fibers fine, flexible and easily separable, like asbestus. Massive varieties have a conchoidal or splintery fracture. Has a smooth, greasy feel. The color of massive varieties is green, bright yellowish green, olive green, to blackish green, or nearly black; the fibrous varieties are apt to be brownish, yellowish brown, pale brown or nearly white. Luster of the massive varieties greasy, wax-like, glimmering and usually feeble to dull; of fibrous varieties pearly to opalescent. Translucent to opaque. Hardness, 2.5–3.0; apparent greater hardness is caused by presence of remains of the original mineral or by infiltrated and deposited silica. Specific gravity somewhat variable, fibrous 2.2–2.4, massive 2.5–2.7. Composition, $H_4Mg_3Si_2O_9 = 2\ H_2O\ .\ 3\ MgO\ .\ 2\ SiO_2$. A small part of the MgO is usually replaced by ferrous oxide, FeO. Before the blowpipe difficultly fusible, fine fibers fuse more readily. In the closed glass tube yields water on ignition. The finely powdered or divided material decomposes in boiling hydrochloric acid with separation of silica but does not gelatinize. The solution may be tested for iron and magnesia. Easily told from epidote and other common green silicates which may resemble it by its greasy feel and softness.

Occurrence. Serpentine is a secondary mineral resulting from the alteration of previously existing silicates containing magnesium. Thus pyroxene, amphibole and especially olivine may be altered to this substance. In the case of olivine the process can be illustrated by the following equation:

$$\begin{array}{ccccccccc} \text{Olivine} & + & \text{Water} & + & \text{Carb. diox.} & = & \text{Serpentine} & + & \text{Magnesite} \\ 2\,Mg_2SiO_4 & + & 2\,H_2O & + & CO_2 & = & H_4Mg_3Si_2O_9 & + & MgCO_3 \end{array}$$

This would explain the frequent association of the mineral magnesite, $MgCO_3$, with serpentine; or it might be taken into solution by the carbonated water and removed.

A still simpler method would be by the action of heated waters containing some soluble silica.

$$3\,Mg_2SiO_4 + 4\,H_2O + SiO_2 = 2\,H_4Mg_3Si_2O_9.$$

Therefore as a product of alteration of such minerals, especially by the action of heated waters, serpentine is a common and widely diffused mineral and is found both in igneous and metamorphic rocks. It may occur disseminated in small scattered masses in the rocks or form large independent bodies of itself, as described further under the chapters dealing with the rocks. Besides the common massive form, many sub-varieties of serpentine are known; the most important of these is the finely fibrous one, often taken for asbestus, which is known as *chrysotile*. It usually occurs in seams in the massive variety. Bright green massive material is known as precious serpentine and is cut for ornamental purposes.

TALC.

General Properties. The exact crystal form of talc is doubtful, but this is not a matter of importance since it so rarely occurs in distinct crystals. It is usually seen in compact or strongly foliated masses, sometimes in scaly or platy aggregates which may be grouped into globular or rosette-like forms. Like mica it has a perfect cleavage in one direction, but the laminæ though flexible are not elastic; it is sectile. It has a soft greasy feel. The cleavage face has a mother of pearl luster. The color is white, often inclining to green; apple-green; sometimes gray to dark gray. Usually translucent. Hardness = 1–1.5, easily scratched with the finger nail. Specific gravity, 2.7–2.8. Streak, light, usually easily seen on dark cloth. Composition, $H_2Mg_3(SiO_3)_4$, acid metasilicate of magnesium. Before the blowpipe it whitens, exfoliates and fuses with difficulty on the edges. Only yields water in the closed glass tube on intense ignition. Scarcely acted on by hydrochloric acid. It is easily recognized by the properties mentioned above.

Occurrence. Talc is a secondary mineral produced by the action of circulating fluids on magnesium silicates, especially those free from alumina, such as olivine, hypersthene and some pyroxenes and amphiboles. The process could be illustrated by the following equation.

$$\begin{array}{lclclclcl}
\text{Enstatite} & + & \text{Water} & + & \text{Carb. diox.} & = & \text{Talc} & + & \text{Magnesite} \\
4\,MgSiO_3 & + & H_2O & + & CO_2 & = & H_2Mg_3(SiO_3)_4 & + & MgCO_3
\end{array}$$

Thus talc occurs at times in the igneous rocks as an alteration product of such silicates, especially in the peridotite and pyroxenite groups. The place, however, where it plays an important function is in the metamorphic rocks, where alone it may form independent masses, as in steatite or soapstone, or be an important component of several varieties of schistose rocks as in talcose schists.

ZEOLITES.

The zeolites are a group of hydrous silicates, composed like the feldspars of aluminum with alkali and alkali-earth metals. They are indeed for the most part secondary minerals which have been formed at the expense of feldspars and feldspathoids by the action of heated circulating waters and steam and are thus chiefly found in igneous and especially volcanic rocks. They do not form a group so closely related in crystallization and other properties as the feldspars, but still, in many ways, they have certain common properties by which they may be distinguished. These will be first described, and then, out of the many species, the individual characters of a few of the most important will be treated.

Group Properties. The zeolites are nearly always well crystallized, the crystals presenting the forms characteristic of the different species. They have a vitreous luster, are usually colorless or white, sometimes tinted yellow or red, like feldspar. They are usually of inferior hardness and can be scratched by the knife. Their specific gravity is low, 2.1–2.4. They fuse very readily before the blowpipe, most of them with intumescence (whence the name, ζεῖν, Greek, to boil), but some quietly, to white glasses or enamels. They dissolve in hydrochloric acid, sometimes gelatinizing and sometimes with separation of slimy silica. Some of the more common varieties are, *analcite*, *natrolite*, *stilbite* and *heulandite*.

Analcite. This zeolite crystallizes in isometric trapezohedrons like garnet, which easily enables one to recognize it. Generally colorless to white. Before the blowpipe first becomes opaque, then fuses quietly to a clear glass, coloring the flame yellow. Dissolves in hydrochloric acid with separation of silica but does not gelatinize. Its composition is $NaAl(SiO_3)_2 + H_2O$.

Natrolite. Crystallizes in orthorhombic prisms which are generally long, slender and even needle-like and arranged in divergent bunches or compacted into fibrous, often radiating masses. Before the blowpipe fuses easily and quietly to a clear glass; fuses in a candle flame. Dissolves in acid with gelatinization. Composition, $Na_2Al(AlO)(SiO_3)_3 + 2\,H_2O$.

Stilbite. Crystallizes in complex monoclinic crystals, which are usually so compounded together that the aggregate has the form of a sheaf. There is a perfect cleavage in one direction and this appears on the side of the sheaf with pearly luster. Sometimes in divergent, sometimes in globular groups. White or red in color. Before the blowpipe swells, intumesces and fuses to a white enamel. Dissolves in acid without gelatinization. Composition,

$$H_4(CaNa_2)Al_2(SiO_3)_6 + 4\,H_2O.$$

Heulandite. Crystallizes in flattened monoclinic crystals which aggregate into compound individuals, the crystals being grown side by side with the flattened surfaces together. There is a perfect cleavage parallel to this flattened side which has a pearly luster. The cleavage plates are often curved and have a lozenge-shaped outline. Blowpipe and chemical characters like stilbite. Composition, $H_4CaAl_2(SiO_3)_6 + 3\,H_2O$.

Occurrence. As stated above, the zeolites are secondary minerals chiefly found in igneous rocks. They are found in these especially when they have been subjected to the action of circulating waters and steam which have attacked the feldspars and feldspathoids. Thus, for example, a mixture of albite and nephelite with water would yield analcite, as follows:

$$\begin{array}{ccccccc} \text{Albite} & + & \text{Nephelite} & + & \text{Water} & = & \text{Analcite} \\ NaAlSi_3O_8 & + & NaAlSiO_4 & + & 2\,H_2O & = & 2\,NaAl(SiO_3)_2 \cdot H_2O \end{array}$$

Thus where feldspathic rocks have been somewhat altered they are very apt to contain zeolites in small amounts scattered through them; in some rare cases it has been found that a considerable part of the rock mass is composed of them, especially of analcite. Ordinarily the presence of these minerals is not to be detected megascopically, though it may be discovered by heating some of the powdered rock in a closed glass tube, when the easy evolution of abundant water would indicate their presence.

Their especial home, from the megascopic point of view, is in the lavas, particularly basaltic ones. Here they are found coating and lining cavities and the sides of jointing planes, and composing the materials of the amygdaloids in lavas, as described under amygdaloidal structure and under basalt. They may be associated with crystals of quartz and of calcite in such occurrences, and, in addition to the common kinds mentioned above, many others may occur whose description must be sought for in the larger manuals on minerals.

Carbonates.

The carbonates are salts of carbonic acid, H_2CO_3, and are secondary minerals, in that their metals have been derived from previously existent minerals acted upon by water and carbon dioxide either from the supply already in the atmosphere or coming from interior sources deep within the earth. The carbonates thus formed have been either deposited directly where we now find them, or, being soluble in water containing carbon dioxide, they have been carried in solution into lakes and into the sea and redeposited by the agencies of organic life in the form of chalk, limestone, etc. The shifting about of carbonates on the earth's surface, owing to their solubility in water containing carbon dioxide, is a geologic process of great importance and gives rise to a variety of products which are described in their appropriate places as rock formations. Here they are treated simply as minerals and out of the considerable number of kinds only two are of such importance that they will be considered in detail — *calcite* and *dolomite.*

CALCITE.

Form. Calcite crystallizes in the rhombohedral system. The crystals are often very fine, perfect, and sometimes of very large size. It displays a great variety of crystal forms many of them being often very complex. Some simple ones are shown in the annexed figures. Fig. 51 is a simple flat rhombohedron, three faces above and three below. Fig. 52 is the unit rhombohedron, so called because the faces are parallel to the cleavage. Fig. 53 is a very acute rhombohedron. Fig. 54 is a very short prism with six prism faces *m* and the flat rhombohedron *e* above and below; Fig. 55 is similar but the prism faces *m* are elongated. Fig. 56 is an acutely pointed form, the scalenohedron. All of these are common crystal forms shown by calcite; they occur when it is found lining cavities in rocks, in druses, in amygdaloids, in geodes and on the surfaces of joint planes and fissures and in caves; in short in all those places where it could be deposited by infiltrating water containing it in solution. As a rock-making mineral it is massive; often crystalline-granular and coarse to fine in structure as in marble, or compact as in ordinary limestone, or loose and powdery in texture as in chalk. It is sometimes spongy in structure as in tufa, or rounded, stalactic, mamillary, etc., as in cave deposits and in concretions, and not uncommonly fibrous.

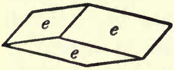


Fig. 51

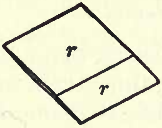


Fig. 52

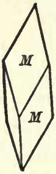


Fig. 53

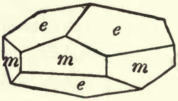


Fig. 54

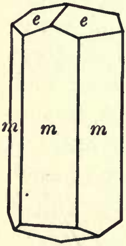


Fig. 55

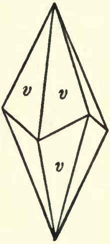


Fig. 56

Cleavage. Calcite has a very perfect rhombohedral cleavage; in three directions parallel to the faces *r* of the crystal shown in Fig. 52. While this is, of course, best produced in isolated crystals it can be well observed on the fractured surfaces of coarsely crystalline massive forms, as in many marbles and related rocks and in the massive calcite of veins. The angles of the face of the rhomb produced by cleavage are just about 78 and 102 degrees, as shown in Fig. 57, and small

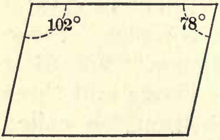


Fig. 57.

cleavage pieces can be readily tested by applying them to the edges of the figure on the paper.

General Properties. The hardness is 3; readily scratched or cut by the knife; chalky varieties are of course softer. The specific gravity is 2.71 if pure. The natural color of calcite is colorless or white but it frequently displays a great variety of exotic colors owing to the presence of impurities; thus it may be reddish or yellowish from iron oxides or gray to black from organic matter, or green, purple, blue, etc., from other substances. Streak, white to gray. The luster of the crystallized calcite is vitreous; of massive forms glimmering to dull. In the same way it varies from transparent to translucent to opaque. Chemical composition, $CaCO_3$; or $CaO \cdot CO_2$. $CaO = 56$ per cent, CO_2, 44 per cent $= 100$.

Before the blowpipe it is infusible, colors the flame reddish yellow and after ignition if placed on moistened yellow turmeric paper colors it brown. Fragments effervesce freely in *cold* (difference from dolomite) very dilute acids.

Occurrence. Calcite is one of the most common and widely diffused of all minerals. It is found in the igneous rocks as the result of alteration of the lime-bearing silicates by waters containing carbon dioxide in solution, other substances being formed as by products at the same time. Thus, for example,

$$\begin{array}{lclclclclclcl}
\text{Pyroxene} & + & \text{Water} & + & \text{Carb. diox.} & = & \text{Calcite} & + & \text{Serpentine} & + & \text{Quartz} \\
3\,CaMg(SiO_3)_2 & + & 2\,H_2O & + & 3\,CO_2 & = & 3\,CaCO_3 & + & H_4Mg_3Si_2O_9 & + & 4\,SiO_2
\end{array}$$

The calcite thus formed may remain for a time in the rock but eventually, as the latter breaks down into soil, it is to a greater or lesser extent removed in solution and carried away. The mineral has also been found to occur very commonly in minute cavities in unaltered igneous rocks, especially intrusive ones, and its origin is probably due to infiltration and deposition of the material from neighboring rock masses. In these cases just mentioned the mineral is ordinarily not observable megascopically, but its presence is easily ascertained by immersing a fragment of the rock in cold dilute acid and seeing if it effervesces and gives off carbonic acid gas. Calcite also occurs in amygdaloidal cavities in lavas, especially in basalts, and often in good crystals.

In the sedimentary and metamorphic rocks calcite plays a much more important part. It is very commonly found distributed through them in fine particles or acting as a cement to the other mineral granules. From this rôle, if we examine a whole series of these rocks, we find it increasing more and more in abundance and importance as a constituent, until finally there are enormous, widely extended rock-masses, such as the chalks, limestones and marbles, composed practically and in some instances wholly of this substance. Such rocks are found described in their appropriate places in this work; it is sufficient here to mention that in the sedimentary rocks calcite plays an important part in chalk, limestone, calcareous marls, calcareous sandstones, etc.; in chemical deposits in calcareous tufas, sinters, stalagmitic deposits, veins, etc., and in the metamorphic rocks in marbles and in rocks which are mixtures of calcite and various silicates.

Determination. Calcite when sufficiently coarsely crystallized is easily recognized by its inferior hardness and rhombohedral cleavage. This is confirmed chemically by its ready solubility in cold dilute acids with effervescence of CO_2 gas and if necessary a test for the presence of lime. For the distinction from dolomite, reference should be made to the description of that mineral.

DOLOMITE.

Form. Dolomite crystallizes in the rhombohedral system and, like calcite, it is found in simple rhombohedral crystals whose faces are parallel to the cleavage; Fig. 52 of calcite. Unlike that mineral it rarely occurs in complicated crystals and the simple rhombohedron, in which it is generally seen when showing outward crystal form, usually has its faces curved as represented in Fig. 58 instead of flat. Moreover the curved crystals are apt to be compound, made up of a number of sub-individuals. This is the way it occurs when lining druses and cavities, but as a rock-making mineral it is nearly always massive, often crystalline-granular and coarse to fine in texture as in some marbles. It is also often compact-massive as in some limestones; more rarely columnar or fibrous.

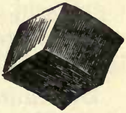


Fig. 58

Cleavage. The cleavage, like that of calcite, is perfect in three directions parallel to the faces of the simple rhombohedron. The angles of the cleavage rhombs differ only a degree or so (74 and 106 degrees, nearly) from those of calcite and therefore by form alone they cannot be distinguished by the eye.

General Properties. The natural color is white and while this is often seen the mineral is very apt to be tinted some exotic color by other substances; thus it may be reddish, brown, greenish, gray or even black. Luster, vitreous, sometimes pearly to dull or glimmering in compact varieties. Translucent to opaque. The hardness is 3.5–4.0, harder than calcite but easily scratched with a knife. Specific gravity, 2.8–2.9. Chemical composition, $CaMg(CO_3)_2$; CaO 30.4, MgO 21.7. CO_2 47.9 = 100. Before the blowpipe infusible, but placed on moist turmeric paper after ignition colors it brown. Does not dissolve or is very little acted upon in cold dilute acid but on boiling effervesces and goes into solution (difference from calcite). The solution may be tested for lime and magnesia as directed in the chapter on mineral tests.

Occurrence. Dolomite occurs as a scattered accessory component of certain crystalline schists and in beds of gypsum, etc., but its chief importance as a rock-making mineral lies in the fact that alone it forms immense extended beds both in the sedimentary series and in the metamorphic rocks. It thus exactly parallels calcite, and in limestones and in marbles we have every degree of transition between these two substances, thus marbles composed of calcite alone, others with increasing amounts of dolomite until pure dolomite marble is reached. This is more fully described under the carbonate rocks.

Determination. The rhombohedral cleavage and inferior hardness separate dolomite, like calcite, from other common rock minerals. The frequent curved surfaces help to distinguish it from calcite but the test with hot and cold acid mentioned above, together with the finding of magnesia in the solution, is the only safe way.

Siderite, Magnesite and Breunerite. As an appendix to calcite and dolomite these carbonates, which are sometimes of local importance, may be mentioned. Siderite or spathic iron ore is $FeCO_3$, ferrous carbonate, while magnesite is magnesium carbonate, $MgCO_3$, and breunerite is an isomorphous mixture of the two, $(MgFe)CO_3$. In crystallization, cleavage, hardness, etc., they closely resemble the other carbonates described. Siderite is usually light to dark brown in color; magnesite white; breunerite brownish. Siderite chiefly occurs more or less massive and impure in certain sedimentary deposits, in the so-called " clay iron stone " and is a valuable ore of iron. Magnesite occurs chiefly in certain metamorphic rocks and is apt to be associated with serpentine, talc, etc. It may be acccompanied or replaced by breunerite.

Sulphates.

The sulphates, like the carbonates, are in general minerals of a secondary nature; the metals they contain have been taken from previously existent minerals, the sulphuric acid has been furnished for the most part by the oxidation of metallic sulphides or by exhalations in regions of igneous activity. With a few exceptions they are readily soluble and the great bulk of them, which has been formed during geologic time, has therefore been transferred to the sea, which, with the salt lakes in the interior of continents, is now the great reservoir of these substances as well as of many other soluble salts such as the chlorides. As rock-making minerals only two of the large number of sulphates known are of importance, *gypsum* and *anhydrite*. Barite, $BaSO_4$, which is one of the few insoluble sulphates, is a very common material in veins and is also found in concretions, but it does not form independent rock-masses or play any rôle as a rock-component as the two first mentioned do.

GYPSUM — SELENITE.

Form. Gypsum crystallizes in the monoclinic system, and the common form of the crystals is shown in Fig. 59. The same crystal is shown in Fig. 60 revolved so that the side face *b* is parallel with the plane of the paper; such crystals may be roughly tested by placing them on the diagram and seeing if the angles coincide. Twin crystals are common and they are apt to assume arrow-head forms as shown in Fig. 61. More commonly as a rock constituent, gypsum occurs massive, foliated often with curved surfaces, or granular to compact and sometimes fibrous.

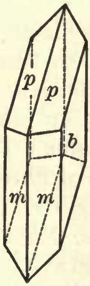


Fig. 59

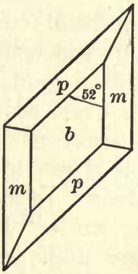


Fig. 60

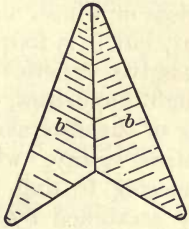


Fig. 61

Cleavage. Gypsum has a perfect cleavage parallel to the side face *b*; by means of it on good material very thin sheets with perfect luster may be split off, almost as in mica. Such sheets will be found to break in one direction in straight lines with a conchoidal fracture; this is due to another cleavage parallel to the vertical edge between *mm.* If such sheets be bent cracks will appear in them making angles of 66 and 114 degrees with the straight fracture edge mentioned above; if the bending parallel to this direction is continued the plate will break with a fibrous fracture, and a cleavage rhomb like that shown in Fig. 62 may be obtained. In massive coarsely crystalline gypsum, these cleavages can usually be readily obtained and furnish one means of helping to identify it; in fibrous material it simply cleaves parallel to the fibers; in the compact massive forms it may happen that no cleavage is seen.

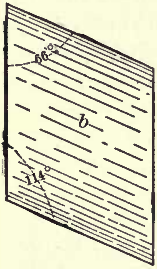


Fig. 62

General Properties. The natural color of gypsum is colorless or white, and crystals are transparent to translucent, but it is frequently tinted reddish or yellowish or in massive varieties may be even red, brown or black through impurities, and translucent to opaque. The luster of the cleavage face *b* is glassy to pearly, of fibrous varieties satiny, while massive forms are glistening, glimmering to dull. Streak, white. Hardness, 1.5–2.0, easily scratched by the finger nail. Specific gravity of pure crystals, 2.32. Chemical composition, hydrous sulphate of calcium, $CaSO_4 + 2\,H_2O$. CaO 32.5, SO_3 46.6, H_2O 20.9 = 100. Before the blowpipe fuses easily and after ignition colors moistened turmeric paper brown. Fused with carbonate of soda and charcoal dust on charcoal and transferred to a moistened surface of silver stains it dark. Finely powdered mineral is readily soluble in boiling dilute hydrochloric acid. Heated intensely in a closed glass tube gives off water and becomes opaque. Heated moderately (not above 200 degrees) it loses some water and becomes plaster of Paris and the powder, if moistened, again takes up water and sets or becomes solid turning back into gypsum. If heated too highly it loses all its water, becomes anhydrite, $CaSO_4$, and is then called dead burnt plaster and does not set as described above.

The occurrence of gypsum is mentioned later in its description as a stratified rock.

ANHYDRITE.

General Properties. Anhydrite crystallizes in the orthorhombic system but in the rocks in which it occurs it is seen in granular to compact masses, less commonly in fibrous or foliated forms. It has a cleavage in three directions at right angles, and if coarsely crystalline this may be observed to produce cube-like forms. Usually white but sometimes tinted as in gypsum; luster of cleavage faces pearly to glassy; in massive varieties varies to dull. Harder than gypsum = 3–3.5 but easily cut by knife. Specific gravity, 2.95. Chemical composition, $CaSO_4$; CaO 41.2, SO_3 58.8 = 100. Blowpipe and other reactions as with gypsum, but it does not yield water in the closed glass tube on heating which is the best distinction from gypsum; the difference in cleavage also aids in the discrimination.

Occurrence. Like gypsum, anhydrite forms interstratified beds in sedimentary formations especially in limestones and shales. It is also found in masses and in geodes in such rocks and is a common associate of rock salt and gypsum.

ROCK SALT — HALITE.

Rock salt, sodium chloride, NaCl, is the only chloride which occurs as a rock-forming constituent in such amounts as to be of importance. It is easily recognized by its cubic crystals, perfect cubic cleavage, solubility and saline taste. Colorless and transparent to white, translucent; frequently tinted various colors by impurities. Hardness = 2.5. Occurs in beds, sometimes of enormous thickness, in the sedimentary formations, usually clays or shales, and is frequently accompanied by gypsum and anhydrite.

CHAPTER V.

THE DETERMINATION OF ROCK MINERALS.

THE more important of the physical properties of the rock minerals have been described in the previous chapter, and in most cases the methods by which these are to be determined have been stated under them. In the present chapter it is proposed to present a number of qualitative chemical tests, which can generally be made with a few reagents and simple apparatus, and which are of great service in mineral determination and in thus aiding to classify rocks. This is followed by a set of tables; one for rough approximations in the field, the other for more complete identifications in the laboratory by means of the properties and methods described.

Chemical Tests.

These consist mainly in observing the effect of acids upon the mineral, whether it is dissolved or only partly attacked or is wholly insoluble; if soluble, or partly so, in ascertaining with certain reagents what substances have gone into solution. These serve to detect the acid radicals and metallic oxides which alone or in combination compose the rock minerals. A few useful additional tests are given.

A. **Powdering the Sample.** The first thing in testing the solubility of minerals is to prepare a finely powdered sample. Small chips, grains or splinters of the substance about the size of wheat grains and as pure as possible are successively crushed and ground to a fine powder, like flour, in a diamond, steel or agate mortar, until a sufficient amount has been produced. It is usually best to crush the fragments in the steel mortar, and unless iron is to be tested for they may be ground in this as well. The finer the powder is ground the more readily it will go into solution; it is therefore generally best to grind it until it no longer feels gritty when a small pinch is rubbed between the fingers.

B. **Treatment with Acid.** A small bulk of the powder prepared as above, about equal to a pea in volume, is put in a test tube, covered with about an inch of distilled water and a few drops of nitric or hydrochloric acid added. Either may be used, but if it is desired to test for phosphorus or chlorine subsequently in the solution the former should be employed. The test tube, if the cold acid has no apparent effect upon the substance, may then be gently heated over the flame of a bunsen burner or lamp of a suitable kind until the liquid is brought to boiling. If the effect is slight or apparently none has been produced more acid is added and the boiling repeated until the substance is brought into solution or it is apparent that it cannot be dissolved.

C. **Carbonic Acids — Carbonates.** If the substance effervesces freely and readily in cold dilute acid it indicates that it is a carbonate and that CO_2 gas is being given off. It is probably calcite. The carbonates of magnesia and iron (dolomite, siderite, etc.) are scarcely acted upon or but very slowly in cold acid but effervesce freely when the liquid is heated. This serves as a convenient means of distinction between calcite and dolomite which may be confirmed by tests for lime and magnesia as given beyond. The rare rock mineral cancrinite, a silicate containing CO_2 also effervesces very slowly in hot dilute acid; the heated solution should be examined in a good light with a lens when a slow persistent evolution of minute bubbles will be seen. In regarding the heated solution care must be taken not to confuse the ebullition of steam bubbles with the effervescence of CO_2 gas; a moment's pause should be given to allow the former to cease.

D. **Soluble Silicates. Gelatinization.** If the substance treated according to A wholly or partly dissolves without effervescence it should be tested for soluble silica. If only partly attacked the insoluble portion should be filtered off and the filtrate used. This is concentrated by boiling it down in the test tube, the latter being continuously and gently shaken to prevent cracking, until the solution is greatly concentrated, if necessary to a few drops. It is then allowed to cool and stand, and if it becomes a jelly the presence of soluble silica is indicated. If the amount of silicate which has gone into solution is relatively large, a jelly will probably form while the solution is being boiled down and is still hot, otherwise the solution must be concentrated and allowed to stand, as just stated; in the latter case care must be taken not to confuse a thickening of the solution from concentration in it of the salts, especially basic salts of iron, with the true jelly of soluble silica. If the solution is carefully carried to dryness and the residue heated for a few moments the salts on being moistened with strong hydrochloric acid and then warmed will go into solution in water while the silica is left as an insoluble residue and may be filtered off. In the filtrate the various metallic bases, aluminum, iron, calcium, etc., which may be in solution, can be tested for by the methods described beyond.

The rock-making silicates which will go into solution on boiling with nitric or hydrochloric acid are nephelite, sodalite, analcite, olivine, chondrodite, serpentine, anorthite, leucite, noselite, stilbite, heulandite and cancrinite. All except serpentine, leucite, analcite, stilbite and heulandite yield gelatinous silica; with these when the liquid is boiled it turns from the milkiness caused by the suspended material to a translucent appearance with slimy silica suspended in it. The bases, however, have gone into solution.

E. **Insoluble Silicates. Fusion.** Most rock-making silicates are insoluble in acids or only partially soluble. To get them into solution so that the bases may be tested for as in the following sections, a preliminary process of fusion with sodium carbonate, Na_2CO_3, must be undertaken. For this purpose some of the powder obtained in A is mixed with about 4–5 times its weight of dry anhydrous sodium carbonate, placed in a platinum crucible or spoon, and gently heated to redness over a Bunsen lamp flame. If no crucible is at hand a coil of platinum wire can be used instead; the mixed powder is made into a thick paste with a little water and a quantity taken on the coil and carefully fused before the blowpipe. A fused bead or mass the size of a large pea may be obtained in this way. The fusion must be conducted until bubbling has ceased.

In this fusion the silicates are decomposed, silica is liberated from them and takes the place of the carbonic acid in the sodium carbonate which is thus converted into sodium silicate. The liberated CO_2 gas is given off with bubbling and frothing of the fusion and this effect is in itself indicative of the presence of silica in the original substance, provided it is known not to come from combined water by previous trial. The reaction might be illustrated in the case of pyroxene as follows:

$$MgCaSi_2O_6 + 2\,Na_2CO_3 = 2\,Na_2SiO_3 + MgO + CaO + 2\,CO_2$$

The fused mass obtained is broken up in a diamond mortar, placed in a test tube, and then treated with acid until dissolved, evaporated and the silica separated and the metallic bases brought into solution just as directed for soluble silicates in D.

If the fusion has been made in a platinum crucible the cake can generally be loosened and removed by boiling it with a little water; if not, it is dissolved with water and acid in the crucible, the latter being set in a beaker or dish.

F. **Alumina.** The filtrate from the silica obtained in D or ED combined, may be tested for alumina. It is heated to boiling after addition of a few drops of nitric acid, and ammonia is added in slight excess. If a white or light-colored, flocculent, gelatinous precipitate forms, this is aluminium hydroxide. If it is reddish brown, then it is wholly or in part ferric hydroxide, indicating the presence of iron, which is very apt to be present in silicates, especially colored ones, and the alumina may be masked.

If much magnesia is present in the mineral its hydroxide may also be precipitated at this point by the ammonia, unless the solutions are rather diluted and a considerable quantity of ammonium chloride or nitrate has been formed by the neutralization of the acid by the ammonia.

Scrape some of the precipitate from the filter paper, transfer it to a clean test tube, or if it is small in amount transfer it paper and all, and cover with about 5 cubic centimeters of water; drop in a piece of pure caustic potash, KOH, about the size of a pea, and boil. The alumina, if present, will go into solution leaving the iron hydroxide undissolved; the latter may be now filtered off. Make the filtrate slightly acid with hydrochloric acid, boil and then add ammonia in slight excess; alumina, if present, will be precipitated as the white flocculent hydroxide.

Alumina can also be detected before the blowpipe by intensely heating the powdered mineral, moistened with cobalt nitrate, on charcoal, when its presence is indicated by the mass turning blue, as mentioned under topaz, cyanite, etc., in the following tables.

G. **Iron.** The detection of this metal has been mentioned above in F. A more delicate method is to add a few drops of potassium ferrocyanide solution to a few drops in water of the final filtrate obtained in D or ED combined, after boiling with a few drops of nitric acid in case hydrochloric was originally used. The formation of a deep Prussian blue precipitate or coloration, if the solutions are very dilute, indicates the presence of iron. The nitric acid converts the ferrous salt in the solution into a ferric one. Potassium *ferro*-cyanide produces a Prussian blue with *ferric* salts, not with ferrous, while conversely potassium *ferri*-cyanide produces the same effect with *ferrous* salts. Thus by testing portions of the original solution of the mineral in hydrochloric acid with these two reagents the state or states of oxidation of the iron in the original mineral can be ascertained.

Iron is also shown when minerals become magnetic after being heated in the reducing flame of the blowpipe.

H. **Calcium.** The ammoniacal filtrate from the hydroxides of alumina and iron obtained in F, or the clear liquid in case ammonia failed to precipitate, may contain lime salts in solution. To prove the presence of lime it should be heated to boiling and some ammonium oxalate added, when the formation of a precipitate of oxalate of lime proves the presence of this element. If it should be desired to further test the solution for magnesia the lime oxalate must be removed by filtration; it is allowed to stand for some time and then filtered; if the filtrate runs through turbid it should be again passed through the paper until the liquid is clear. To this a little more ammonium oxalate is added to prove the complete precipitation of the lime.

I. **Magnesium.** Ordinarily this element should not be tested for until the alumina, iron and lime have been removed, as directed in F and H, or their absence ascertained. To the solution thus obtained some sodium phosphate and a considerable quantity of strong ammonia are added. The formation of a precipitate, ammonium magnesium phosphate, proves the presence of this element. If a precipitate does not form at once it is not, however, safe to consider magnesia absent, for if the amount is small and the solution warm it may not appear until the liquid has become cold and has stood for some time. It is then apt to appear as a crystalline precipitate attached to the walls of the vessel.

J. **Sodium.** A mineral containing sodium when heated before the blowpipe colors the flame bright yellow. The best effect is obtained with silicates when the powdered mineral is previously mixed with an equal volume of powdered gypsum and a little of this taken upon a clean moistened platinum wire which has been previously tested. The reaction is, however, so delicate and produced so strongly by minute quantities of the element or accidental traces that great judgment must be used in employing it. It is only when the coloration is very intense and prolonged that the mineral should be inferred to contain soda as an essential oxide.

K. **Potassium.** This element may be detected by the violet color it communicates to the Bunsen or blowpipe flame. In silicates it is best obtained by powdering the mineral and mixing it with gypsum, as mentioned under sodium in J. The flame color is delicate and entirely obscured by any sodium present; in this case it can be seen by viewing it through a piece of thick, dark blue glass which cuts off all but the potash flame. Through this it will appear of a violet or reddish purple.

Another test is to take a small portion of the final filtrate obtained in D or ED combined, evaporate it to a very small volume, add an equal volume of alcohol and if turbid filter it. Then add a few drops of hydrochlorplatinic acid, H_2PtCl_6, and if a heavy yellow or orange colored crystalline precipitate, potassium platinic chloride, K_2PtCl_6, forms it shows the presence of this element. No ammonium salt must be present or it will yield a similar precipitate.

L. **Hydrogen — Water.** If a little of the powdered mineral be placed in a glass tube, one end of which has been closed by fusion and drawing off, and gently heated below redness, the evolution of water, which collects on the upper walls of the tube, shows that it contains loosely attached *water of crystallization.* This occurs with zeolites, such as analcite, $NaAlSi_2O_6 + H_2O$, and with gypsum, $CaSO_4 + 2\,H_2O$. On the other hand, some minerals, and many silicates are among them, contain hydrogen and oxygen firmly attached in the form of *hydroxyl* – OH, and this is only given off as water at a very high heat. Indeed with some, as for instance staurolite and talc, $Mg_3Si_4O_{10}(OH)_2$, it is necessary to subject the assay to intense ignition by heating it white hot before the blowpipe before the water is given off. This difference in behavior will often serve as a useful test in determining minerals. Many minerals which contain hydroxyl also contain fluorine and in this case it will be often found that the water evolved in the tube gives an acid reaction to test paper and the glass may be etched. Unless the latter occurs the test is not however decisive of the absence or presence of fluorine.

M. **Fluorine.** This is best tested for as described under topaz, on page 81, in a bulb tube with sodium metaphosphate.

N. **Chlorine.** This occurs in rock salt, apatite and sodalite. The test is the precipitation of chlorine as silver chloride, AgCl, in the solution by addition of a few drops of silver nitrate. The white precipitate turns bluish gray on exposure to light. The test for chlorine is very delicate and slight impurities may cause a faint opalescence in the liquid on addition of the silver salt. Rock salt is easily told by its solubility in water, taste and associations. Apatite usually contains only a very little chlorine yielding a faint test, or chlorine may be wanting in it. Sodalite dissolves in dilute nitric acid and silver nitrate produces in this a considerable precipitate of the chloride; the nitric acid solution also yields gelatinous silica as in D; these tests suffice to identify the mineral.

O. **Sulphuric Acid.** Barium chloride produces in the solution containing a sulphate a heavy white precipitate of barium sulphate, $BaSO_4$, insoluble in hydrochloric or nitric acid. Gypsum, anhydrite and noselite contain sulphuric acid; they dissolve in hydrochloric acid and it may be tested for as above. Noselite also yields gelatinous silica, as in D, and the two reactions serve to identify it.

P. **Phosphoric Acid.** Dissolve the powdered mineral (see A) in nitric acid and add some solution of ammonium molybdate, a yellow precipitate of ammonium phosphomolybdate shows the presence of phosphorus. This test is very delicate. It should be conducted with cold or nearly cold solutions. The precipitate is soluble in excess of ammonia. If it is desired to make this test in a mixture of minerals, as in a fine-grained rock for instance, and silica may be in the solution, it is best to evaporate the latter and get rid of the silica as directed in D. The phosphoric acid can then be tested for in the filtrate acidified with nitric acid. Apatite is the only common rock-making mineral containing phosphoric acid, and its presence in rocks and soils can usually be shown by this test when it cannot be detected megascopically.

Tables for the Megascopic Determination of Rock Minerals.

The two following tables will be found useful in helping to identify the commoner rock-making minerals. Beside those given in the tables there are many less common minerals which enter into the composition of rocks and which may at times become of local importance. This is especially true in metamorphic limestones and schists. Some of the more important of them have been given in the preceding chapter on the characters of minerals, but only about fifty minerals or mineral groups constituting the kinds which are ordinarily met with in megascopic rock study are here included. The tables can only be used to distinguish from one another the minerals which are named in them; they cannot in general be used to distinguish them from all other minerals. If doubt arises and a mineral seems to be other than any of those described here the larger manuals of descriptive and determinative mineralogy must be consulted for its identification.

Table 1. This is based solely on the most obvious and easily determinable physical properties and includes about thirty common minerals or mineral groups. It may

often be used to advantage in the field. The only apparatus required in its use are a lens, pocket knife and fragments of quartz and feldspar, in addition to the hammers usually carried. It will be of advantage to have one blade of the knife magnetized. The streak or color of the powdered mineral can be tested by grinding a small piece to powder between two hammer faces, pouring it on a piece of white paper and rubbing the dust with the finger to observe the color produced. A piece may be cracked into smaller grains and these examined with the lens to observe the cleavage if it is not well shown by the mineral on the fractured rock surface. The transparency or translucency, if not obvious in the mineral in the rock, may be tested by holding a fragment or sliver against the light and observing if light is transmitted through its thinnest edges. The hardness is best tested on a smooth lustrous cleavage face with the knife point or a sharp-pointed fragment of quartz or feldspar, substances which are usually readily obtainable.

Table 2. This includes about fifty of the prominent rock minerals or mineral groups whose characters are treated in the foregoing descriptive portion. It requires for its use some of the simpler apparatus and reagents found in every chemical and mineralogical laboratory and the knowledge of how to use them. They have been already mentioned on page 12.

The table is based upon those of the Brush-Penfield Determinative Mineralogy which have been modified to meet the demands of this particular place, and if further information is desired that manual may be consulted to advantage.

This table is much more complete and certain in its identification than Table 1 and should always be used in preference to it when possible. Table 1 is to be considered a more or less rough method of approximation to be used in the field or when no apparatus or reagents are at hand.

It should be again repeated that the table cannot be used for the identification of all minerals which occur in rocks but only to distinguish the commoner ones, mentioned in it, from one another. In most cases the identification of the mineral is complete, but instances may occur where some comparatively rare one will give similar reactions. Thus the rare mineral aragonite would lead to the same place as calcite, but reference to the description of the latter would show at once that it differs markedly in other properties, such as cleavage and crystallization. This will be usually found to be the case, and if further information is desired it must be sought elsewhere. But within the limits imposed the table should serve a useful purpose to the student of rocks.

TABLE 1.

The mineral has a fine cleavage in one direction; is sometimes micaceous and may be split into thin leaves by the use of the knife point. Sec. 1 below.

Has a good cleavage in two directions. Sec. 2.

Has a good cleavage in three directions, forming cubes or rhombs. Sec. 3.

Has a fine fibrous structure and cleavage. Sec. 4.

No apparent good cleavage. Sec. 5.

SEC. 1. *Cleavage in one direction.*

A. Micaceous. Cleavage leaves tough, flexible, *elastic.* Occurs in crystals, shreds, flakes. Black, brown, gray or white. Transparent-translucent. *Mica,* p. 50.

B. Micaceous. Cleavage leaves tough, flexible, *non-elastic.* In crystals, shreds, masses. Usually green to dark green. *Chlorite,* p. 98.

C. Often micaceous. Leaves flexible but *non-elastic.* Greasy feel, very soft, marks cloth. White, greenish, gray. Usually in foliated masses. Translucent. *Talc,* p. 102.

D. Leaves somewhat flexible but showing cross cleavage cracks when bent; in one direction fibrous, the other brittle forming rhombs. Soft, scratched by finger nail, but not greasy in feel. Usually colorless, white or reddish; transparent to translucent. In crystals, masses, seams. *Gypsum,* p. 111.

E. Leaves have a brilliant metallic luster, like polished steel. *Hematite* (micaceous variety) p. 91.

F. Leaves brittle; lozenge shaped outline. Usually white, translucent. Scratched by the knife. Crystals in cavities. *Heulandite,* p. 104.

G. Not micaceous, massive, brittle. Very hard, not scratched by knife or feldspar. Yellowish green to dark green, translucent. In crystals or masses. *Epidote,* p. 73.

SEC. 2. *Cleavage in two directions.*

A. Two cleavages at or very nearly at 90 degrees. Brittle, hard, not scratched by knife but by quartz. Usually of a light color, white, pink to red or gray, translucent. In crystals, grains, masses. *Feldspar,* p. 34.

B. Usually of a dark color, greenish to black; in grains or short prisms; sometimes light colored in metamorphic rocks and then often elongated columnar in cleavage direction. Cleavage good but not eminent; prismatic. Cleavage angles 87 and 93 degrees. Usually scratched by feldspar. *Pyroxene,* p. 55.

C. Usually of a dark color, greenish to black. Apt to be in crystals elongated or bladed in cleavage direction. Sometimes light colored in metamorphic rocks. Cleavage very good with shining surface. Cleavage angles 55 and 125 degrees. Usually scratched by feldspar. *Amphibole,* p. 60.

SEC. 3. *Cleavage in three directions.*

A. Cleavages not at right angles, forming rhombs. Easily scratched by knife. Usually white, sometimes tinted various shades to black; transparent to translucent. In crystals, masses, veins, etc. *Calcite,* p. 105, or *Dolomite,* p. 108. (If rhombic surfaces of crystals are curved, probably dolomite.)

B. Cleavages at right angles forming cubes, soluble, strong saline taste. Transparent colorless or white, rarely tinted. In crystalline masses. *Halite,* rock salt, p. 113.

C. Cleavage apparently as above. No perceptible taste. Easily scratched by the knife. White, bluish. In crystalline masses. *Anhydrite,* p. 113.

D. Apparent cleavages sometimes forming rhombs, sometimes apparently cubic. Very hard, scratches quartz easily. In hexagonal crystals, grains or lumps of a dark, smoky, or bluish gray; more or less translucent. *Corundum,* p. 86.

SEC. 4. *Has a fine fibrous or columnar structure*

A. In opaque brown to black masses. Streak yellow-brown. *Limonite,* p. 93.

B. In opaque red-brown to black masses. Streak brownish red. *Hematite,* p. 91.

C. White or reddish; translucent. Brittle. Often radially fibrous. Sometimes showing slender prismatic crystals. Difficultly scratched by the knife. Occurs in cavities, veins or seams. *Natrolite*, p. 103.

D. White or reddish; translucent or transparent. Brittle. Often radially fibrous. Compound crystals often sheaf shaped. Scratched by knife. In cavities, veins or seams. *Stilbite*, p. 103.

E. Shreds easily into fine, flexible fibers like cotton or silk. White or light gray. *a. Hornblende asbestus*, page 65. *b.* White to yellowish brown; silky; generally in veins in or associated with serpentine. *Chrysotile* (serpentine) *asbestus*, page 101.

F. White or pale colors. Translucent. Brittle. Easily scratched by knife but not by finger nail. In masses. *Calcite*, p. 105.

G. White to pale red. Silky luster, translucent. Brittle, soft, scratched by finger nail. In masses and seams. *Gypsum*, p. 111.

SEC. 5. *Without good or apparent cleavage*

A. Opaque, brass-yellow crystals with metallic luster. Not scratched by the knife. *Pyrite*, p. 94.

B. Opaque, earthy, brown to brown-black masses. Streak yellow-brown. Scratched by the knife. *Limonite*, p. 93.

C. Opaque, reddish brown to black masses, or crystals and grains, iron black with metallic luster. Streak brownish red. Scratched by the knife. *Hematite*, p. 91.

D. Opaque, iron black masses, grains or octahedrons with metallic luster. Streak black. Magnetic. Not scratched by the knife. *Magnetite*, p. 89.

E. Opaque, black grains or masses often with reddish tone. Luster metallic to submetallic. Streak black to reddish black. Not noticeably magnetic. Scarcely or not scratched by the knife. *Ilmenite*, p. 90.

F. In garnet-shaped crystals or spherical. Usually dark red to black and translucent. Brittle. Not scratched by feldspar. *Garnet*, p. 70.

G. In garnet-shaped crystals. Colorless or white to gray white, translucent. Not scratched by knife but by feldspar. *Leucite*, p. 49, or *Analcite*, p. 103.

H. In transparent to translucent crystals or grains of a light yellowish- or bottle-green color. Not scratched by feldspar. *Olivine*, p. 67.

I. In prismatic crystals, generally slender, shiny and black with triangular cross section. Not scratched by quartz. *Tourmaline*, p. 78.

J. In grains, masses or hexagonal, pyramidal crystals. Conchoidal fracture. Greasy to glassy luster. Colorless, white, smoky, dark; transparent to translucent. Not scratched by feldspar. *Quartz,* p. 83.

K. In grains or masses, rarely in crystals with rectangular or hexagonal sections. Conchoidal fracture. Greasy, oily luster. White, gray or reddish; translucent. Scratched by feldspar. *Nephelite,* p. 47.

L. In grains or masses, generally of a bright blue color. *Sodalite,* p. 48.

M. In masses, of a dark or yellowish green, easily scratched or cut by knife. *Serpentine,* p. 100.

N. In masses, often somewhat foliated. Greasy feel; very soft, marks cloth. White, greenish, gray. *Talc,* p. 102.

O. In hexagonal crystals, grains or lumps. Dark smoky or bluish gray; translucent. Very hard, not scratched by quartz, garnet or tourmaline. *Corundum,* p. 86.

P. In masses, compact or chalky. Friable, very soft, easily cut by finger nail. Rubbed between the fingers has a soft soapy feel. *Kaolin,* p. 96.

TABLE 2

1 *A.* The mineral has a metallic luster or is opaque and gives a dark or strongly colored streak. 2.*
B. The mineral is without metallic luster or is transparent or translucent on very thin edges and its streak is white or light-colored. 6.*

2 *A.* Heated in the blowpipe flame the mineral burns and gives off sulphurous fumes. Has a brass yellow color. *Pyrite,* p. 94.
B. Heated in the reducing blowpipe flame becomes magnetic when cold. Not brassy in appearance. Infusible or very difficultly so. Iron oxides. 3.

3 *A.* Is magnetic without heating. *Magnetite* (and in part *Ilmenite*), p. 89.
B. Is only magnetic after heating. 4.

4 *A.* Heated in the closed glass tube gives water. *Limonite,* p. 93.
B Gives little or no water. 5.

5 *A.* Reacts for titanium. *Ilmenite,* p. 90.
B. No reaction for titanium. Streak brownish or Indian red. *Hematite,* p. 91.

6 *A.* Fusible before the blowpipe (fusibility 1–5). 7.
B. Infusible or very difficultly fusible. 17.

*** The appended number in each case refers to that in front of a succeeding section.**

7 *A.* Become magnetic after heating before the blowpipe in reducing flame. 8.
B. Do not become magnetic. 11.

8 *A.* Soluble in hydrochloric acid with separation of silica, sometimes gelatinous. 9.
B. Insoluble in hydrochloric acid or only slightly acted on. 10.

9 *A.* Micaceous or foliated. *Mica* (Biotite or Lepidomelane), p. 50.
B. Isometric crystals. Gelatinizes imperfectly. *Garnet* (Andradite), p. 70.
C. Gelatinizes. *Olivine*, rich in iron — *Fayalite*, p. 67.

10 *A.* Micaceous — difficultly fusible. *Biotite*, p. 50.
B. Isometric crystals or spherical in shape. After fusion gelatinizes with HCl. Dark red color. *Garnet* (Almandite), p. 70.
C. Quietly and difficultly fusible. Greenish black or bronze-brown. Good cleavage. *Pyroxene* (Hypersthene), p. 55.
D. Fuses with intumescence coloring flame strong yellow. Black. Prismatic cleavage, angle 55 degrees. *Amphibole* (Arfvedsonite), p. 60.
E. Fuses quietly, coloring flame yellow. Black, prismatic cleavage, 93 degrees. *Pyroxene* (Aegirite), p. 55.

11 *A.* Readily and completely soluble in water; has a saline taste. *Halite*, rock-salt, p. 113.
B. Difficultly soluble in water. After intense ignition colors moistened turmeric paper brown.
  a. Gives much water in closed glass tube, *Gypsum*, p. 111.
  b. Gives little or no water in closed tube, *Anhydrite*. p. 113.
C. Soluble in hydrochloric acid without gelatinizing or separation of silica on evaporation. A drop of sulphuric acid in the solution precipitates calcium sulphate. *Apatite*, p. 95.
D. Soluble in hydrochloric acid with gelatinization.
  a. Heated in closed glass tube gives off water. 12.
  b. Heated as above yields little or no water. 13.
E. Soluble in hydrochloric acid, silica separates but no jelly forms.
  a. Heated in closed glass tube gives off water. 14.
  b. Heated as above yields little or no water. 15.
F. Insoluble in hydrochloric acid. 16.

12 *A.* Fuses quietly to a clear transparent glass. White or colorless; in slender crystals or fibrous bunches. *Natrolite*, see Zeolites, p. 103.
B. A fragment in warm dilute hydrochloric acid gives off minute bubbles of CO_2 gas. *Cancrinite*, see Feldspathoids, p. 48.

13

- *A.* Fuse rather easily before the blowpipe, coloring the flame strong yellow. Dissolve easily in very dilute nitric acid and gelatinize.
  - *a.* The nitric acid solution gives a precipitate with silver nitrate solution (page **121**). Color usually blue. *Sodalite,* p. 48.
  - *b.* The nitric acid solution gives a precipitate with barium chloride solution. *Hauynite-Noselite,* p. 48.
  - *c.* No reaction with silver nitrate or barium chloride. *Nephelite.* p. 47.
- *B.* Difficultly soluble in hydrochloric acid and colors the flame very little. Has a good cleavage in two directions. *Anorthite,* see Feldspars, p. 34.

14

- *A.* Usually in greenish masses, compact, greasy, sometimes fibrous. Difficultly fusible. *Serpentine,* p. 100.
- *B.* Fuses quietly to a clear glass coloring flame yellow. Generally in colorless or white garnet-like crystals. *Analcite,* p. 103.
- *C.* Fuses with swelling and intumescence. Commonly in sheaf-like or radiated crystals. *Stilbite,* p. 103.
- *D.* Fuses as in *C.* Crystals have a fine cleavage with pearly luster and lozenge-shaped section. *Heulandite,* p. 104.

15

- *A.* Fuses quietly to a glassy globule. Slowly acted on by hydrochloric acid. Good cleavage in two directions; one generally shows fine parallel twinning lines. Often grayish or bluish with a play of colors. *Labradorite,* see Feldspars, p. 34.
- *B.* Fuses quietly to white globule. Easily soluble in hydrochloric acid; solution evaporated to dryness, residue moistened with little hydrochloric and dissolved in water and filtered, ammonia produces little or no precipitate. *Wollastonite,* $CaSiO_3$, a variety of Pyroxene, generally of a white color.

16

- *A.* Micaceous. Cleave into thin flexible elastic plates in one direction. *Micas,* p. 50.
- *B.* Micaceous. Cleaves into thin plates, flexible but not elastic, micaceous. Very soft and has a greasy feel. Color white, gray or greenish. *Talc,* p. 102.
- *C.* Cleavable, micaceous, but cleavage plates not elastic, though flexible. Soft, but not so soft as talc. Color green, usually rather dark green. *Chlorite,* p. 98.
- *D.* Not micaceous. Solid and brittle. Good cleavage in two directions at or about 90 degrees. Generally light colored, red or gray. Hard, cannot be scratched by knife. Difficultly fusible. *Feldspar,* p. 34.
- *E.* Before the blowpipe fuses with swelling and bubbling. Very hard, scratches feldspar. Generally in black columnar crystals, sometimes red or green. No cleavage. *Tourmaline,* p. 78.

F. Fuses quietly. Gelatinizes with hydrochloric acid after fusion. Crystals as on page 70 or in spherical forms. Very hard. No good cleavage. *Garnet,* p. 70.

16 *G.* Fuses with swelling and intumescence to a black slaggy mass which gelatinizes in hydrochloric acid. Powdered mineral on intense heating in closed glass tube yields a little water. Yellowish to blackish green. *Epidote,* p. 73.

H. Fuses quietly or with little intumescence. Generally scratched by feldspar.
  - *a.* Prismatic cleavage with angle of 87 degrees. *Pyroxene* p. 55.
  - *b.* Prismatic cleavage with angle of 55 degrees. *Amphibole,* p. 60.

I. Fuses with intumescence to a greenish or brownish glass which will gelatinize with hydrochloric acid. *Vesuvianite,* p. 75.

17 *A.* After intense ignition before the blowpipe gives a brown stain when placed on moistened turmeric paper. 18.

B. Dissolves in hydrochloric acid but without gelatinizing or yielding a residue of silica on evaporation. 19.

C. *a.* Dissolves in hydrochloric acid and gelatinizes. *Olivine,* p. 67.
  b. Reacts for fluorine (see topaz 22 F.). *Chondrodite,* p. 82.

D. Dissolves in hydrochloric acid, does not gelatinize but silica separates. 20.

E. Insoluble in hydrochloric acid.
  - *a.* Can be scratched by glass or a knife point. 21.
  - *b.* Cannot be scratched by glass or the knife. 22.

18 *A.* Effervesces freely in *cold* dilute acid. *Calcite,* p. 105.

B. Effervesces freely in *hot* but not in cold acid. *Dolomite,* p. 108.

19 *A.* Heated in the reducing blowpipe flame becomes magnetic.
  - *a.* Little or no water in closed tube; streak brown-red. *Hematite,* p. 91.
  - *b.* Water in closed glass tube; streak yellow-brown. *Limonite,* p. 93.

B. In hexagonal crystals usually. Gives reactions for phosphorus. A little dilute sulphuric acid gives a precipitate of white $CaSO_4$, in the cold concentrated solution of mineral in hydrochloric acid. Readily scratched by the knife. *Apatite,* p. 95.

20 *A.* Commonly in compact green masses. Sometimes fibrous. like asbestus, then white or brownish or yellowish. Greasy feeling, easily scratched by knife. *Serpentine,* p. 100.

B. In spherical or garnet-shaped crystals. White to gray *Leucite,* p. 49.

21
- *A. Micaceous.* Cleavage leaves tough and elastic. *Micas,* p. 50.
- *B. Micaceous.* Cleavage leaves tough and flexible but not elastic. Intense ignition in closed tube gives water. Color green. *Chlorite,* p. 98.
- *C. Very soft* and has a greasy feeling. *Talc,* p. 102.
- *D.* Clay-like, compact or mealy. Leaves undissolved silica in the phosphorus salt bead. Gives water in the closed glass tube. *Kaolin,* p. 96.

22
- *A.* Extremely hard. Scratches quartz. Generally has a parting that looks like cleavage. *Corundum,* p. 86.
- *B.* No cleavage; conchoidal fracture. Scratches feldspar. Sometimes in hexagonal crystals with pyramid at end. *Quartz,* p. 83.
- *C.* Prismatic cleavage. Becomes black before the blowpipe and very fine splinters fuse with difficulty. Brown to green or greenish black. *Pyroxene* (enstatite-hypersthene), p. 55.
- *D.* Good cleavage in two directions at 90 degrees or nearly so. Generally light in color, red or gray. Scratched by quartz. Fusibility = 5. *Feldspars,* p. 34.
- *E.* In prismatic crystals, often twinned; scratches quartz; red-brown to brownish black; intense ignition in closed tube gives a little water. *Staurolite,* p. 76.
- *F.* Reaction for *fluorine* when heated in tube with soda metaphosphate. With cobalt nitrate reacts for alumina (see *G* below). One good cleavage. Scratches quartz. *Topaz,* p. 81.
- *G.* Powdered mineral moistened with cobalt nitrate and intensely heated by the blowpipe on charcoal becomes blue (*alumina*); *a,* in stout rectangular prisms, often full of impurities, not scratched by knife. *Andalusite,* p. 77; *b,* in bladed, generally blue, crystals; scratched by knife parallel to cleavage, but not at right angles to it. *Cyanite,* p. 78.
- *H.* No crystal form or structure. Effervesces in Na_2CO_3 bead. Yields a little water in closed tube on intense ignition. *Opal,* etc., p. 86.

PART III.

ROCKS.

CHAPTER VI.

GENERAL PETROLOGY OF IGNEOUS ROCKS.

It has been previously stated that all rocks may be divided into three great natural groups, the igneous, the sedimentary and the metamorphic. The *igneous* are those which have been formed by the solidification of molten masses from within the earth. With reference to their origin they have also at times been called the *primary* rocks because the material which composes the other two classes has been originally derived from igneous rocks which, from time to time, have been formed either in or on the upper part of the earth's crust or from the earth's original crust itself. And if we follow the view that the earth was once molten, the original cooling crust must have been of the nature of igneous rock. Hence in this sense the igneous rocks are the primary ones.

Distinguishing Characters of Igneous Rocks. The characters of the igneous rocks, by which they may be distinguished from the sedimentary and metamorphic ones, are of two kinds — field characters and specimen characters. The field characters are those which can only be observed in the field by studying the mass of rock in its relation to surrounding masses, or in other words its mode of occurrence, that is, whether it is a dike, a laccolith, a lava sheet, etc. These modes of occurrence will be presently described. If that of a given rock mass can be clearly determined it indicates, more definitely than anything else, if it is igneous in origin or not.

But very often it happens that the boundaries of a rock mass are so covered or obscured that its relations to the surrounding rocks and its mode of occurrence cannot be told, or it is often necessary to determine the nature of a specimen which has been removed from a parent mass which is not accessible for study. In this case we are compelled to fall back upon those characters of the rock which are inherent, and to be observed by an examination of the material of the outcrop or specimen. Of these there are three principal ones which distinguish the igneous from the sedimentary and metamorphic rocks. They are:

a. Entire absence of fossils.

b. The material composition.

c. The arrangement of the material, texture or structure.

The first character is an obvious one, but it is largely of negative value since many sedimentary and most metamorphic rocks do not contain fossils.

The second refers to whether the rock contains glass or is wholly made up of mineral grains, and if the latter, the kinds and relative amounts of the minerals present. If a rock is made up wholly or in part of glass it is certainly of igneous origin. The presence of certain minerals is also proof of igneous origin, but no general rule by which a rock may be certainly stated to be of igneous origin from its mineral composition can be given. This would have to be done from a knowledge of the different kinds of igneous rocks themselves, as they are described in a following chapter. The third character is that the igneous rocks present a homogeneous appearance; that a surface of the rock in one direction is like a surface in any other direction — that they do not show the stratified, banded, or foliated structures which are characteristic of the sedimentary and metamorphic rocks. In addition there are certain minor structures which sometimes appear in igneous rocks, such as the amygdaloidal, which are highly characteristic and will be described later.

There are exceptions to the rules given above in *a* and *c*, but at the outset it is better for the student to consider them as if absolute, and the exceptions, which will be discussed in their appropriate places, will take care of themselves.

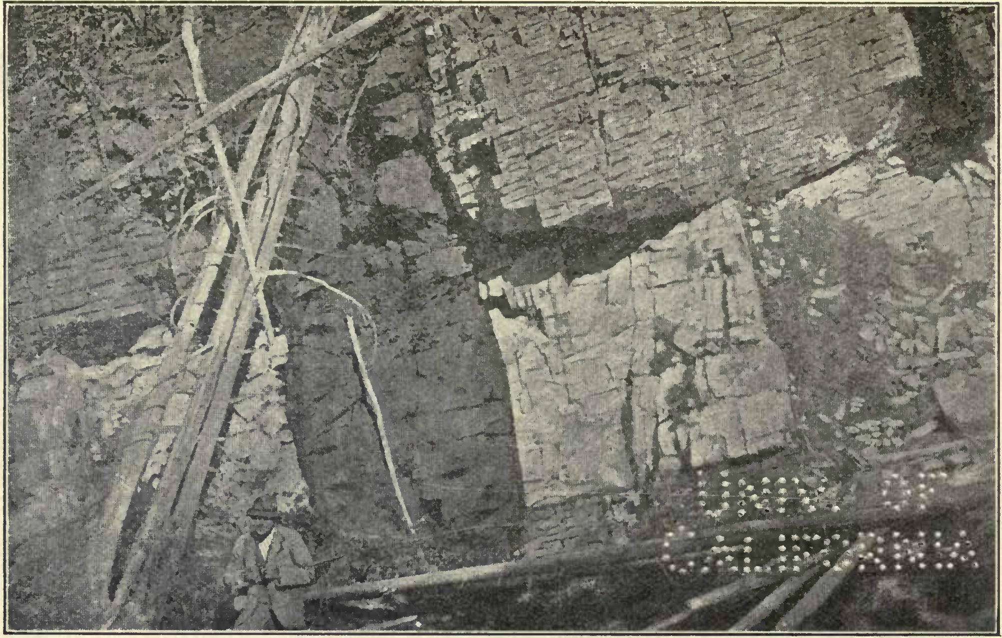
Occurrences of Igneous Rocks.

There are two chief modes of occurrence of igneous rocks recognized by geologists, the *extrusive* and the *intrusive.* In the extrusive the molten mass or magma rising from depths below has attained the surface, come out upon it, solidified and formed the rock. They are also called *effusive* and sometimes *volcanic* rocks, though they are not always connected with volcanoes. In the case of the intrusive rocks the magma has stopped before attaining the surface and has cooled and solidified, surrounded by other rock masses of the earth's upper crust. Each of these cases has a number of recognized subdivisions; with the extrusive rocks depending on the conditions under which the magma was ejected and with the intrusive rocks on the relation which the mass bears to the rocks which surround it. Following the course of the magma upward we will describe first the intrusive and then the extrusive modes of occurrence.

Intrusive Modes of Occurrence. These are *dikes, sheets, laccoliths, necks, stocks* and *bathyliths.* Various other modes have been recognized and described, but for simplicity's sake they may be regarded as modifications of these which have just been mentioned. The simplest form of intrusion is that of the dike, and this will be described first.

Dikes. A dike is the result of the simple filling of a fissure in rock masses by molten magma from below which there solidified. In shape, its extension in length and breadth is great as compared with its thickness. It

PLATE 2.



DIKE, CUTTING INTRUSIVE SHEET AND STRATIFIED BEDS, CASTLE MOUNTAIN, MONTANA.

(U. S. Geological Survey.)

may " cut, " that is, pass through, other igneous rocks or through sedimentary or metamorphic ones, whatever the material was in which the fissure was formed. In passing through sedimentary rocks it always cuts at some angle across the planes of stratification; if parallel to them it becomes an intrusive sheet. A dike may be of all sizes from a fraction of an inch in thickness up to half a mile; from two or three feet up to twenty are the ones most commonly observed; it may be but a yard or two long as exposed on the surface, or it may be many miles; a great dike in the north of England has been traced over a hundred miles. The plane of extension of a dike in most cases appears to be vertical or nearly so; often it is inclined at varying angles to the vertical plane. This angle of inclination is called the *hade* of the dike, and the direction which its outcrop takes in intersecting the horizontal plane is called its *trend*. Dikes may have attained the surface and given rise to lava outflows, or they may not and have been exposed only by subsequent erosion. In the processes of erosion they may have resisted better than the surrounding rock and thus project as walls, a common feature; or they may have resisted less well and have become ditches, which is less common. Dikes very often show pronouncedly the columnar structure described later, the columns lying at right angles to the walls. Where dikes have cut through sedimentary rocks they have often changed and altered them for some distance in the manner described under contact metamorphism. A view of a dike cutting a sheet of igneous rock and stratified beds is seen in Plate 2.

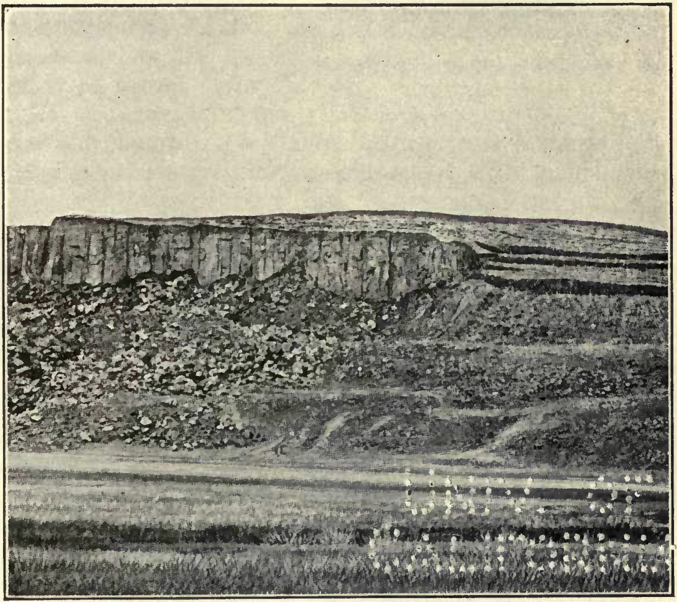
Intrusive Sheets. It frequently happens that where molten magma is being forced upward through, or into, stratified rocks, that it attains a place where the conditions are such that it is easiest for it to spread out in a layer between the sedimentary beds. This frequently happens where the beds are weak and easily penetrated, as in shales, thinly bedded sandstones, etc. The form of such a mass is like that of a dike, but unlike the latter it lies concordantly along the planes of stratification. Such sheets may be only a foot or less in thickness, and from this up to several hundred feet or even more: they may spread over many miles in extent. Like dikes they often show a columnar structure, the columns being perpendicular to the upper and lower surfaces and thus often vertical. Sometimes they break, dike-like, across the strata and are continued along a new horizon. They are usually of the same hard, firm rock at top and bottom, and to some extent have altered and changed the sedimentary beds both above and below them: these characters distinguish them from surface flows of lavas which have been buried by later deposits of sediment upon them. They are most apt to occur in connection with larger and more important intrusions of magma, such as stocks, laccoliths, etc., as accompanying or dependent features. In regions where thick extensive sheets occur and the strata have been dislocated, faulted, and upturned they often give rise, through erosion, to prominent topographic features as illustrated in the trap ridges of southern New England, northern New Jersey, and in Scotland at Edinburgh and in many other places. In Great Britain and frequently in Canada an intrusive sheet is called a *sill.* Examples are shown on Plates 2 and 3.

Laccoliths. These are great lenticular masses of igneous rock lying between stratified beds which infold them. If in the forming of an intrusive sheet the supply of material from below goes on faster than it can spread at a given thickness laterally, the strata above will begin to arch up, and if the process continues a great thick half lens, flat below and rounded above, of liquid rock, will be formed.* A cross section of such a one is shown in Fig. 63. They are apt to run out into intrusive sheets or be accompanied by them. Also on the flanks of folding, uplifting mountain ranges where the folding strata are subjected to horizontal pressure they may tend to open,

---

* Increased viscosity of magma also helps in this result.

PLATE 3.



LACCOLITH, AND INTRUSIVE SHEETS OF BASALT, IN SANDSTONES, SHONKIN SAG, MONTANA.

(U. S. Geological Survey.)

and such openings be filled with magma from below in measure as they open, as illustrated in Fig. 64. In general, laccoliths are more or less circular or oval in ground plan, and while sometimes symmetrical as in the diagrams they are apt not to be so but more or less distorted in shape. The floor may be flat or tilted as in the figures. They differ from intrusive sheets only in being extremely thick in comparison with their lateral extension, and all gradations between the two may be found. They may be a mile or more in thickness and a number of miles in diameter, or but a few hundred yards across. The beds above are usually stretched, thinned and broken in the process of formation. Like intrusive sheets they alter and change the strata above and below by contact metamorphism. They are most apt to occur in weak beds of shale, etc., the stronger, thicker beds of sandstone and limestone being up-arched. The best examples that are known are found in the region of the Rocky Mountains, where in many places they are not uncommon.

Fig. 63. Cross Section of a Laccolith

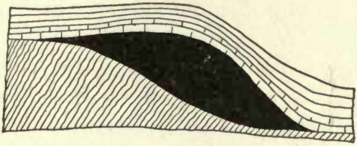


Fig. 64. Section of an Inclined Laccolith

Cases have been described where the roof of a laccolith has been ruptured and driven upward by the magma rising like a plug through the strata. It has been suggested that such forms be called *bysmaliths* (Greek, plug rocks). It has also been suggested that when a body of magma is injected into the stratified rocks like a laccolith, but of indefinite shape and without the relations to the planes of stratification which a laccolith has, such a mass be termed a *chonolith* (Greek, mold — used in casting — rock).

Necks. When a volcano ceases its activity and becomes extinct the column of magma, occupying the conduit leading to unknown depths below, may solidify and form a mass of igneous rock. Erosion may cut away a great part of the light porous ashes and lavas, leaving this more solid and resistant rock projecting, as shown by the heavy line *abc* in Fig. 65. Or the level of erosion may continue to descend into the rocks which form the basement on which the volcano is built, all traces of the ashes, lavas, etc., being swept away and only this mass being left to mark its former site. Such a mass of rock is known as a volcanic *neck*. It is commonly more or less circular in ground plan and may be from a few hundred yards up to a mile or more in diameter. The rocks about them are apt to be fissured and filled with dikes and in many cases, if stratified, with intrusive sheets.

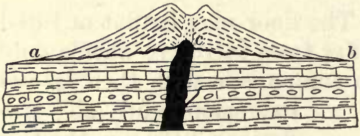


Fig. 65. Section Through a Volcano

Stocks. This term has been applied to large bodies of intrusive rock which in the form of magma have ascended into the upper region of the earth's crust and there solidified. They have become visible by extended erosion and tend to have a more or less circular or elliptic ground plan. Their plane of contact cuts across the inclosing rocks, is more or less irregular, and the mass may widen in extent as it descends. Their size may be anything from a few hundred yards to many miles in extent. Since they are apt to form protuberant topographic features through erosion they are sometimes, especially in Great Britain, called *bosses*. The distinction from a volcanic neck is not one of size alone, though necks tend to be smaller than stocks, but lies in the fact that the term neck is employed only when there is evidence that there has been extrusive volcanic activity from it. Some stocks were doubtless necks, but this cannot now be

PLATE 4.

UNIV. OF CALIFORNIA

SQUARE BUTTE, A DENUDED LACCOLITH, HIGHWOOD MOUNTAINS, MONTANA.

(U. S. Geological Survey.)

proved. The granite hills of New England, of Scotland and of other old eroded mountain regions are often stocks or bosses.

Bathyliths. This term is used in a general way to designate those huge irregular masses of igneous rock, which, underlying the sedimentary and metamorphic ones or sometimes cutting through them, have been exposed by erosion. They are seen in the oldest exposed areas of the crust where they are characteristically accompanied or surrounded by metamorphic rocks, as in eastern Canada, or in mountainous regions where they form the central cores or masses of the ranges, as in the Alps. They differ chiefly from stocks in their much greater size, as they are not infrequently many thousands of square miles in surface area.

While some stocks are clearly intrusive and have displaced the rocks whose site they occupy, the mode of formation of others and of bathyliths is still a subject of speculation. Some have held that they have attained their position by melting and assimilating the previous formation and thus replacing it, while others have urged the view that it has been ruptured, uplifted and driven out by the invading mass and then eroded away. Various modifications of these views have been suggested, but geologic science is not yet in a position to pronounce definitely upon their correctness.

Extrusive Igneous Rocks. For petrographical purposes two chief modes of extrusion may be recognized, the *quiet* one, giving rise to outwellings of magma in the liquid state which then solidifies to rock, and the *explosive*, in which the material by the violent action of gases is projected into the air and falls in a solid but fragmental form.

Quiet Eruption; Lava Flows. When the magma rises to the surfaces and outpours it is then called *lava*. The solidified material is often called a sheet of lava or *extrusive* sheet. Such flows often come from volcanoes; the extrusions of some, like those now active in Hawaii, being wholly of this nature, while in others they alternate with or succeed projections of explosive fragmental material.

In other cases they are not connected with volcanic eruptions but have taken place as quiet outwellings from numerous fissures. This has sometimes occurred on a huge scale, as in the Columbia River region of the northwestern United States, in western India and in the north of the British Isles. In these regions the repeated lava flows are thousands of feet in depth and cover areas of from 100,000 to as much as 200,000 square miles.

Not infrequently sheets of lava have sunk below sea-level and been covered by deposits, or they have originated on the sea floor and have been covered. Such buried extrusive sheets are distinguished from intrusive ones by the fact that they have not altered or changed the sediments above them by contact metamorphism (qu. vid.), and their upper surfaces usually show the structures common to the surface of lavas, such as the vesicular, amygdaloidal, scoriaceous and ropy ones described later.

Explosive Eruption; Tuffs and Breccias. When a magma attains the surface in the canal of a volcano it may give rise to quiet flows of lavas as mentioned above, or if its viscosity is sufficient and it is charged with vapors under great tension it will give rise to explosive activity,

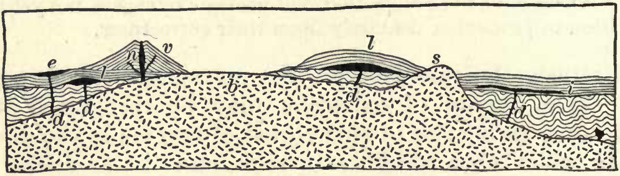


Fig. 66. Diagram to Illustrate the Occurrence of Igneous Rocks : *b*, bathylith; *s*, stock; *n*, volcanic neck forming *v*, a volcano with tuffs and breccias; *l*, *l*, laccoliths; *i*, intrusive sheet; *e*, extrusive sheet; *d*, *d*, dikes. Horizontal distance shown, thirty miles; vertical distance, three miles.

and the material will be projected into the air to fall in solid fragmental form. Owing to the expansion of the vapors, chiefly steam, the projected pieces usually have a more or less pronounced vesicular structure, and vary in size from those weighing perhaps several hundred pounds to dust so fine that it floats for long periods in the air. According to size these may be roughly classified as follows. Pieces the size of an apple and upward are called *volcanic bombs;* those the size of nuts are termed *lapilli;* those the size of small peas or shot *volcanic ashes;* while the finest is *volcanic dust.* The coarser material, the bombs, ashes and lapilli, falls around the vent and builds up the cone; the lighter ashes and dust, carried by air currents, tend to fall after these and at greater distances. The beds of coarser material thus produced are termed volcanic conglomerate or more commonly *volcanic breccia,* while the finer is known as *tuff.**

General Characters of Igneous Rocks.

Since igneous rocks are formed by the consolidation of molten magmas it is evident that the nature of a rock produced must in large measure depend upon the chemical composition of the magma which forms it. For most rocks are composed of mineral grains, and the kinds and relative amounts of these must depend upon the kinds and relative amounts of the chemical elements which form the molten fluid. It is pertinent therefore to inquire what the general chemical character of the earth's magmas is like and if there are any general rules which appear to govern their composition.

Chemical Composition of Magmas. We cannot of course subject a molten magma directly to investigation, but this may be essentially done if an average sample of an igneous rock is subjected to chemical analysis. Several thousand such analyses have been made of rocks from all parts of the world, and these results show, as might be expected from the discussion given on page 17 and following, that the magmas and therefore the rocks are

---

* (Volcanic tuff was formerly commonly called *volcanic tufa,* but at the present time it is customary to restrict the word *tufa* to deposits from aqueous solution, especially those of a calcareous nature.)

made up of the following oxides: *silica*, SiO_2; *alumina*, Al_2O_3; iron oxides, both *ferric*, Fe_2O_3, and *ferrous*, FeO; *magnesia*, MgO; *lime*, CaO; *soda*, Na_2O, and *potash*, K_2O. Other oxides, including water, are also present but in such relatively small amounts that they do not exercise any controlling influence and may be neglected.

The variations in chemical composition which are shown in the magmas are in a general way exhibited in the following table of selected analyses.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO_2 . . .	56.6	65.5	72.5	65.1	56.0	49.2	40.1	38.4
Al_2O_3 . .	22.4	17.8	13.1	16.2	15.6	12.0	7.8	0.3
Fe_2O_3 . .	1.8	0.7	1.7	1.1	1.2	2.8	7.3	3.4
FeO . . .	0.8	1.2	1.0	3.2	6.3	8.8	8.6	6.7
MgO . . .	1.3	1.0	0.6	2.3	6.8	9.3	23.7	45.2
CaO . . .	0.3	1.9	1.0	4.0	7.3	10.6	6.5	0.4
Na_2O. . .	8.5	5.6	4.2	4.0	2.2	1.9	1.2	0.1
K_2O . . .	7.3	5.6	4.9	2.5	1.3	1.7	0.5	
Rest . . .	1.4	0.7	0.7	1.6	3.3	3.2	4.5	5.7
Total .	100.4	100.0	99.7	100.0	100.0	99.5	100.2	100.2

I, Nephelite Syenite, Serra di Monchique, Portugal; II, Syenite, Highwood Mountains, Montana; III, Granite, Castle Mountains, Montana; IV, Quartz Diorite, Electric Peak, Yellowstone Park; V, Diorite, Montgomery County, Maryland; VI, Gabbro, Red Mountains, Montana; VII, Peridotite, Devonshire, England; VIII, Dunite, Tulameen River, British Columbia.

Variation of Magmas and Mineral Composition. It is not to be understood that all the different varieties of magmas are represented by these analyses; they are only selected to show the most prominent and general features of variation. Certain of these can be readily seen by observing the table. Thus in the first three analyses it is evident that silica, alumina and the alkalies, potash and soda, are the chief oxides composing them, while lime, iron and magnesia play a very subordinate part.

It is therefore evident that if such magmas should crystallize into minerals they would be mostly composed of alkalic feldspars because these are composed of silica, alumina and alkalies. Again, if we regard the amounts of silica in these three and remember that orthoclase, potash feldspar, contains about 65 per cent of silica and albite, the soda feldspar, about 68, it is clear that in No. III there is more silica than needed to form the alkalies and alumina into feldspars, and there will therefore be extra silica which will crystallize as free quartz. In No. I, on the contrary, there is not enough silica to turn all of the alumina and alkalies into feldspar, and a certain amount of some mineral, such as nephelite, which contains these oxides in combination with a smaller amount of silica must be formed to compensate this deficiency. In No. II the per cent of silica is very nearly that required for the pure feldspars, and these will make up the great bulk of the rock with little either of quartz on the one hand, or of nephelite on the other.

If now we turn our attention to the oxides of lime, iron and magnesia, it is evident that the minerals which they produce, such as biotite, hornblende and pyroxene, will have but a subordinate rôle in the first three rocks, but in Nos. IV–IX these oxides continually increase while silica alumina and alkalies also decrease, and eventually the last two vanish and the silica becomes very low. Expressing this in terms of minerals, if the magmas crystallized, it is evident that in these four the *ferromagnesian* minerals — those containing iron or magnesia or more commonly both — such as pyroxene, amphibole or olivine, would play an increasingly important rôle, and that the last rock would be wholly composed of them, while feldspars correspondingly become less important and ultimately disappear.

In this connection the variation of lime deserves a separate word because lime has a dual function: it may form a feldspar with alumina and silica which then commonly combines with soda feldspar to form plagioclase (soda-lime feldspar), or it may enter into the ferromagnesian minerals, pyroxene and amphibole. It generally does both and thus for a time as we follow the table of analyses from left to right, as lime increases, the quantity of both plagioclase and of ferromagnesian minerals increases also. Coincident with this the alumina also increases somewhat.

Variation shown by Diagrams. The facts which have been stated above may be shown in a graphic manner by means of a simple diagram, Fig. 67. Thus in the place of the analyses of the foregoing table we may draw vertical lines, one for each analysis, at equal distances apart and on each line set off a vertical distance in millimeters equal to the per cents of each oxide in the analysis. Through these points lines are drawn corresponding to each oxide, the iron and magnesia from the similarity of function they exhibit being united in one line. The equal distances for each analysis at the foot of the diagram thus serve as abscissas and the percentages are ordinates, while the connecting lines approach curves which show the mutual relations of the oxides. In the description of the variation of the oxides it was pointed out how this caused a corresponding variation in the minerals produced by the crystallization of the magmas composed of these oxides. By considering the relative amounts of the important minerals which each type of analysis would produce we can con-

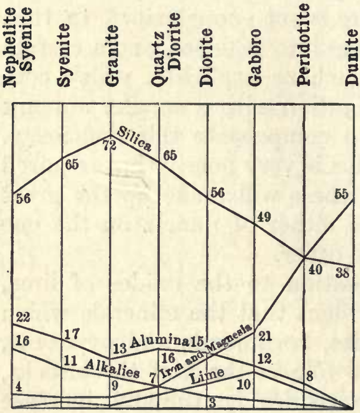
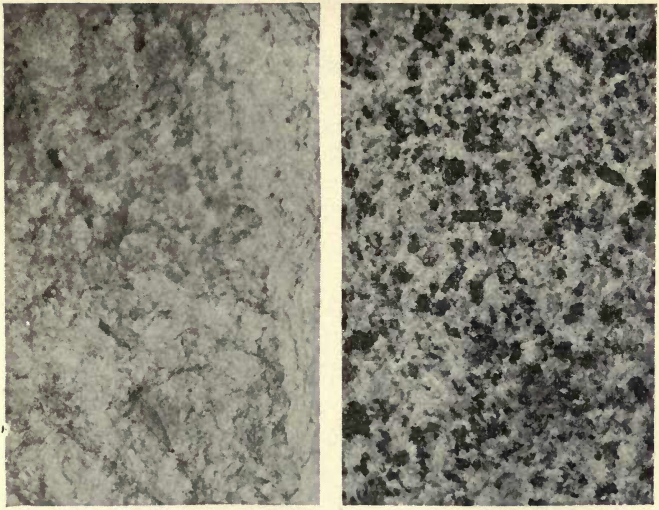
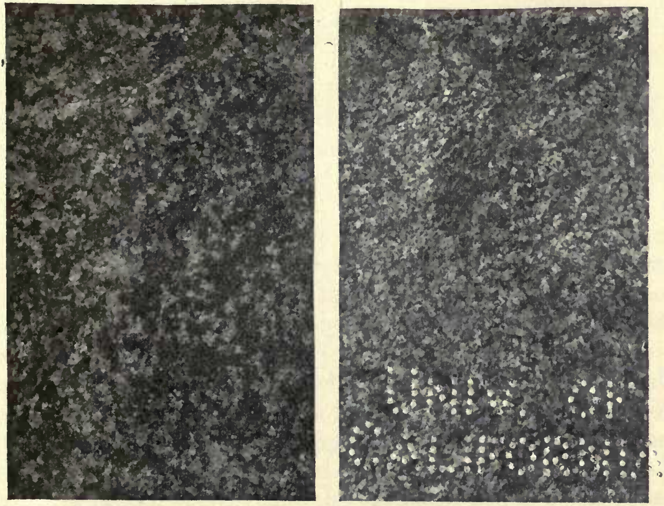


Fig. 67. Diagram to Illustrate Chemical Variation of Igneous Rocks

PLATE 5.



A. Anorthosite, all Feldspar. B. Syenite, mostly Feldspar.



C. Diorite, some Feldspar. D. Peridotite, no Feldspar.

CONTRAST OF FELDSPATHIC AND FERROMAGNESIAN ROCKS.

struct a diagram, Fig. 68, which will show the variation of the minerals in a general way in the common rocks. It also shows the relative proportions of the minerals in the more common and important kinds of igneous rocks,

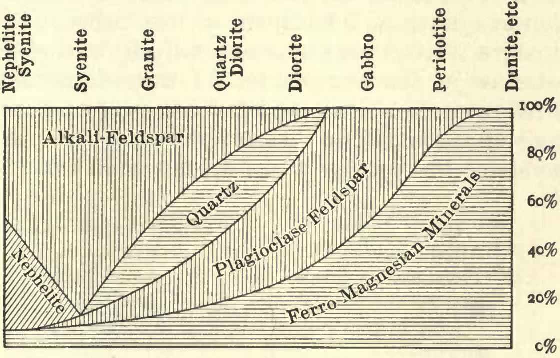


Fig. 68. Diagram to Illustrate the Variations and Relative Proportions of the Minerals Composing the Important Igneous Rocks.

and it serves as a basis for their classification as will be explained later. The relative proportions of the minerals are given in the vertical direction, the variation and passage of one kind of rock into another in the horizontal direction.

It should be repeated that these diagrams and the table of analyses are not to be taken in a hard and fast manner as representing the limits of variation and all the possible mineral combinations of igneous rocks. This would be very wide of the truth. Other analyses might be selected which would yield different diagrams, and if of rare and uncommon rocks, they might be very different indeed, but in a general way these may be accepted as showing the more important chemical and mineralogical features which distinguish the common kinds of igneous rocks from one another.

Minerals of Igneous Rocks. From what has been stated in the foregoing sections it is evident that the more important minerals which compose the igneous rocks are the feldspars, quartz and the ferromagnesian group. For purposes of classification to be explained later it is convenient to contrast the ferromagnesian on the one hand with the quartz and feldspars on the other. Recalling that silica (SiO_2) and alumina (Al_2O_3) are prominent substances in the composition of these latter minerals, and following American petrographic usage, we may term this group the *sal*ic one. More specifically the prominent minerals of the igneous rocks are given in the following table:

SALIC GROUP.	FERROMAGNESIAN GROUP.
Alkalic Feldspar	Pyroxenes
Plagioclase Feldspar	Amphiboles
Quartz	Biotite
	Olivine
Nephelite	
Sodalite	Iron Ores
Corundum	

The last three in the salic group are of much less importance than the first three on account of their restricted occurrence; the iron ores, hematite, ilmenite and magnetite, though so widely distributed that nearly all igneous rocks contain one or more of them, are of less importance than the other ferromagnesian minerals because they usually form only a very small proportion of all the minerals in the rocks. A mineral, like these, which may be quite evenly distributed through a rock but makes only a small part of its mass is called an *accessory component* in contradistinction to those which form its main bulk and are termed *chief or essential components*.

The chemical and physical characters of the minerals mentioned in the above list have been described under their appropriate headings in Part II, to which reference may be made, for further information concerning them.

Order of Crystallization. If a polished surface of a coarse-grained rock be attentively studied with a lens, or better if a thin section be observed under the microscope, it will usually be found that there are more or less distinct evidences that all the minerals composing it have not crystallized simultaneously but successively. Thus in Fig. 69 the crystals of biotite mica (M) contain grains and octahedrons of black iron ore, magnetite; they occur also in the other minerals. They are evidently older than the mica because they are inclosed by it. The mica is older than the soda-lime feldspars or plagioclases (P) because it abuts into them with its own crystal faces or is partly inclosed by them as they grow around the already formed crystals. In the same way the plagioclase has its own form as regards the alkali feldspar, orthoclase (O) and the quartz (Q), which surround it, and is therefore judged to be older than they are. When the orthoclase and quartz are considered they do not show any crystal boundaries with respect to one another, and their crystallization is therefore judged to be more nearly simul-

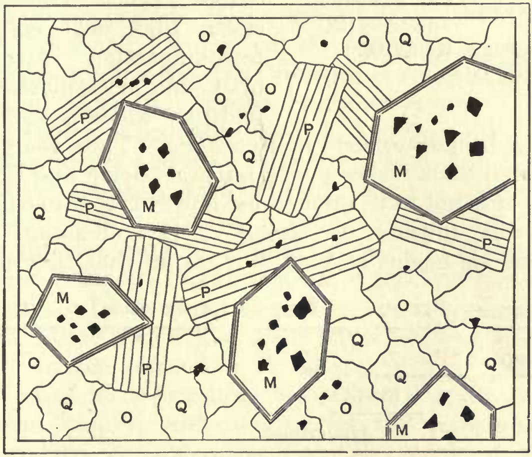
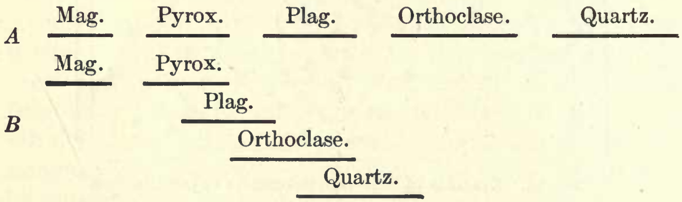


Fig. 69. Diagram to Illustrate Successive Crystallization

taneous. The order of crystallization as thus worked out in this particular case is: first, magnetite, then biotite mica, then plagioclase, and lastly orthoclase and quartz.

The studies which have been made of igneous rocks teach that in general the order of crystallization is: first, the oxides or ores of iron, then ferromagnesian minerals, then soda-lime feldspars, then alkalic feldspars (and feldspathoids) and lastly quartz. One observes from this, as illustrated in the adjoining table, that the process begins with metallic oxides which contain no silica, that next come the ferromagnesian minerals, ortho and metasilicates, then feldspars which contain more silica and finally quartz or free silica. Thus there tends to crystallize out successively minerals richer and richer in silica. It is not to be understood however that one mineral necessarily finishes its period of crystallization before another one begins as in A, but rather that they overlap as in B, that is, that one may begin before another has finished, and continue after the former has ceased. Experience shows that with orthoclase and quartz the overlap is so great that they crystallize nearly simultaneously, only orthoclase usually begins and quartz finishes.

1. Magnetite, Fe_3O_4.
2. Pyroxene, $(MgFe)Ca(SiO_3)_2$.
3. Plagioclase, $\left\{\begin{array}{l} mCaAl_2Si_2O_8. \\ nNaAlSi_3O_8. \end{array}\right.$
4. Orthoclase, $KAlSi_3O_8$.
5. Quartz, SiO_2.



Insolubility vs. Infusibility. A molten silicate magma is to be regarded as a complex solution of some compounds in others, like a solution of mixed salts in some solvent such as water. As the heated solution cools, a point is reached where some compound, or mineral, becomes insoluble in the resulting solution and it therefore crystallizes out. The statement that is sometimes made that the minerals crystallize in the order of their fusibility is entirely wrong; thus from the preceding paragraph we see that pyroxene crystallizes before quartz; now pyroxene is rather readily fusible before the blowpipe, while quartz is infusible. It is not therefore a question of infusibility but of solubility which determines the order of crystallization.

Influence of Mineralizers. Experience teaches us that those magmas which attain the surface in volcanoes and in lava flows contain large quantities of volatile substances, especially water vapor, which they give off, frequently with explosive violence. It was formerly considered that the magmas imbibed these from the moisture laden rocks with which they came in contact on their way to the surface. At present these volatile substances are generally held to be wholly or in large part of magmatic origin, that is, original constituents of the earth's interior molten masses, contained therein under pressure. Without further regard to the theories of how they came to be there we know that the magmas contain them and that they are of great importance in a number of ways in the formation of igneous rocks. The most important of these is water, but carbon dioxide, fluorine, boric acid, sulphur and chlorine are also prominent and may produce important results. The work of various investigators, especially the French, has shown, that while some minerals such as pyroxene, magnetite, lime feldspar, olivine and nephelite may be artificially produced by fusing their constituents together and allowing the molten mass to cool slowly, other minerals such as hornblende, biotite, orthoclase and quartz do not form in dry fusions in the same way. For their production more or less of the volatile substances mentioned above must be present, especially water vapor. These substances appear to act in two ways: in one in a chemical manner since some minerals, such as biotite and hornblende, always contain small quantities of water (in the form of hydroxyl, – OH) or fluorine or both, and these are consequently necessary for their production; and second, in a physical manner in that they lower the melting point of the fusion and greatly increase its fluidity. Thus orthoclase, albite and quartz which have extremely high melting points but only crystallize at much lower temperatures, in a dry fusion become so viscous on cooling that they are unable to crystallize and therefore solidify as glasses. The addition of water under pressure lowers the temperature of solidification and increases the fluidity or mobility of the melted mass and permits such movement of the molecules that they can arrange themselves in crystal form, and the above minerals are produced. These substances then, such as water, fluorine, etc., which exert so important a function in processes of crystallization and on the formation of igneous rocks are called *mineralizers.* As crystallization progresses, the amount of them, beyond what is chemically (and to some extent mechanically) retained in the minerals, is gradually excluded from the solidifying rock mass to play an active rôle in new and important processes, such as the formation of pegmatites, contact metamorphism and others which will be described later in their appropriate places.

Texture of Igneous Rocks.

It has been pointed out that igneous rocks vary in the kinds and proportions of the minerals that compose them and that this variance is mainly due to the chemical composition of the magmas from which they are derived. Another important way in which these rocks vary is in their *texture.* Thus one rock may be made up of mineral grains so large that the different minerals are easily distinguished, while in another the grains are so small as to defy identification by the eye or simple lens. Again the grains may be approximately all of about one size or they may vary in size, some being relatively large while the rest are minute. Or again the conditions may have been such that the magma had no opportunity to crystallize but solidified as a simple glass, or to only partly crystallize and formed a mixture of glass and crystals. Such variations for the most part are independent of chemical composition, they depend upon the *physical conditions* under which the molten mass has solidified, and thus a magma of a given composition may appear in any one of the states mentioned above if subjected to the proper conditions.

The characteristic features which a rock exhibits in this respect constitute its *texture*, and rocks are distinguished and classified in one way according to their textures, just as in another way they are distinguished and classified according to their mineral composition.

Factors influencing Texture. If a strong hot solution of a salt, such as common alum in water, is allowed to cool very slowly and regularly, comparatively few centers of crystallization will be set up, and the few resulting crystals will have a long period of growth and will be of good size. If, on the contrary, the cooling is very rapid a great number of centers of crystallization will form, the period of growth will be short and a great number of very small crystals will result. The same is true in the molten liquids from which the igneous rocks are formed. If the cooling has progressed with great slowness and regularity then coarse-grained rocks are produced; if the cooling is rapid then they are fine-grained and the cooling may take place so quickly that there is no opportunity for complete crystallization, and rocks wholly or in part composed of glass will result. The *rate of cooling* then is a prominent, and in fact the most prominent, factor in the production of rock texture. In addition to the temperature there has been a tendency in the past to ascribe also a prominent rôle to the *pressure*. The idea involved is that if a magma remained liquid within the earth at a given temperature and if for any reason the pressure increases, a point will be eventually reached where it will be forced to crystallize and become solid, since in so doing its volume would be reduced. Decrease of temperature and increase of pressure would then work together. While this may be true in theory it does not seem probable that the pressures obtaining in the upper region of the crust are a very prominent factor in this direction, since geological observation has shown that a particular variety of texture can be found unchanged through a range of 10,000 feet vertical. Still it cannot be denied that pressure probably has some influence on the process of crystallization and the production of rock texture.

The *presence of mineralizers,* especially water, has undoubtedly a strong influence on the texture, particularly in the siliceous rocks, for this greatly increases the fluidity of such magmas and, as they cool down and the crystallizing points of the different minerals are reached, they still retain their mobility instead of becoming stiffly viscous. This increases the range of movement of the mineral molecules forming, and enables larger crystals to grow and a coarser texture to be produced. As we shall see later this reaches its maximum in the pegmatite dikes.

In connection with what has just been stated *chemical composition* of the magmas has a certain influence in producing texture. This shows itself in two ways. Those magmas which are deficient in silica and especially those which contain much iron and magnesia and which are shown in the right hand side of the diagrams given on a previous page remain liquid, without becoming stiffly viscous, to much lower temperatures than those with high silica which are found expressed in the middle of the diagrams. This liquid condition enables them to crystallize more freely and to form in consequence coarse-textured rocks under circumstances where the siliceous magmas would produce only types fine-grained in texture or even glassy from inability to crystallize completely, owing to increasing viscosity. The other way in which chemical composition influences texture is this. Differences in composition in the magmas mean of course differences in the kinds of minerals which they produce. Different minerals crystallize in different shapes and although, owing to interference with one another, they may not form in perfect crystals, they tend to take such shapes. Some form tabular shapes, others spherical or cuboidal grains or elongated prisms. Thus, while the general size of such grains may remain the same throughout a mass of rock, such differences in shape will produce corresponding differences in what we may call the pattern or *fabric* of the rock and thus influence its texture.

Relation of Texture to Geologic Mode of Occurrence. It is evident that the condition most favorable for the production of coarse-textured rocks — conditions described in the preceding discussion as slow cooling, pressure and the presence of mineralizers — will, in general, be best realized when the magma is in large mass and deeply buried in the earth's crust so that it is completely enveloped by surrounding rock masses. The heavy cover retains the heat and the mineralizers and gives in part the pressure. Such igneous rocks, formed in depth, will only become exposed to our observation when continued erosion has carried away the superincumbent material. They are often therefore called *plutonic* or *abyssal* and sometimes *massive* rocks, and referring to what has been described as the modes of occurrence of the igneous rocks it can be seen that bathyliths, stocks and the lower part of volcanic necks may be particularly expected to exhibit such texture and nearly always do so.

On the other hand, when the magmas attain the surface and are forced out in volcanic eruptions, lava flows, etc., entirely different conditions will prevail; there is no cover to retain the heat and the cooling in consequence is rapid. Also the pressure has been relieved, and with loss of cover and pressure the mineralizers quickly depart. As a result fine-grained, dense, compact textures are formed, or the cooling may be so rapid that crystallization may fail to occur, either wholly or in part, and rocks entirely or partly composed of glass may be produced. When rocks are more or less glassy it is in general very good evidence that they solidified as surface lavas.

In the smaller intrusive bodies, such as the dikes, sheets and laccoliths, the conditions in general are between the two sets just described. The volume relative to the surrounding rocks is less, the loss of heat and mineralizers more rapid than in the stocks and bathyliths, and, since in general the depth is less, the pressure is diminished. Thus the textures are usually between those of the larger abyssal masses and the effusive lavas. But the conditions in these occurrences are apt to be very variable, and in accord with this we find the textures sometimes dense like the effusives — but very rarely glassy — and sometimes coarse-granular like the larger abyssal masses. In them, too, the function of chemical composition described in the preceding section is often most strongly displayed. Thus highly siliceous dikes and sheets of fine grain will be found associated under the same geological conditions with other ones low in silica and high in iron and magnesia of relatively much coarser grain.

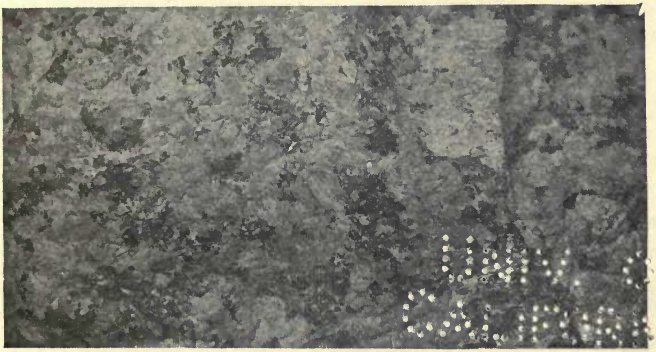
It is especially in these occurrences and in the surface lavas that the *porphyritic texture*, to be presently described, is most liable to be found.

Textures of Igneous Rocks. Based on the principles which have been enunciated in the foregoing sections the textures of igneous rocks for megascopic study may be classified as follows:

Grained. All sizes of grain large enough to be seen with the unaided eye. Example, ordinary granite.

1. Fine Grain.

2. Medium Grain.



3. Coarse Grain.

EVEN-GRANULAR TEXTURE.

Dense (aphanitic). The rock is crystalline, i.e. not glassy, but the grains are too fine to be perceived by the eye. Example, many felsites.

Glassy. The rock can be distinctly seen to be wholly or in part composed of glass, as in obsidian.

The distinctions stated above relate in part to its *crystallinity* or degree of crystallization, for all grades of transition between rocks composed wholly of glass, partly of glass and partly of crystals and wholly of crystals exist, though to be perceived by the unaided eye the glass must form a great or the greater part of the rock. It relates also in part to the absolute sizes of the crystal grains or what we may term the *granularity*.

The phanerocrystalline (Greek, φανερός, visible) rocks according to the size of grain can be divided as follows: (See Figs. 1, 2 and 3, Plate 6.)

Fine-grained, the average size of the particles less than 1 millimeter or as fine as fine shot.

Medium-grained, between 1 and 5 millimeters.

Coarse-grained, greater than 5 millimeters or as great as or greater than peas.

But another very important feature of texture is that of the pattern or *fabric* and this, for megascopic work, is chiefly due to the *relative sizes* of the crystal grains in a given rock. There are two chief kinds of fabric which may be distinguished:

Even-granular fabric (or texture), grains of approximately the same general size.

Porphyritic fabric (or texture), grains of a larger size contrasted with finer ones or with glass.

Even-granular Texture. While this means that in a given rock the crystal grains have approximately the same general size, as may be seen by referring to Plate 6, it does not mean that they have necessarily the same shape. Careful examination of granites which have this texture will show that the dark mica is in many cases present in well formed hexagonal tablets or crystals, while the feldspars and quartz are in shapeless masses, or the feldspar tends to have rough tabular or brick-like shapes. This depends on the order of crystallization as previously explained.

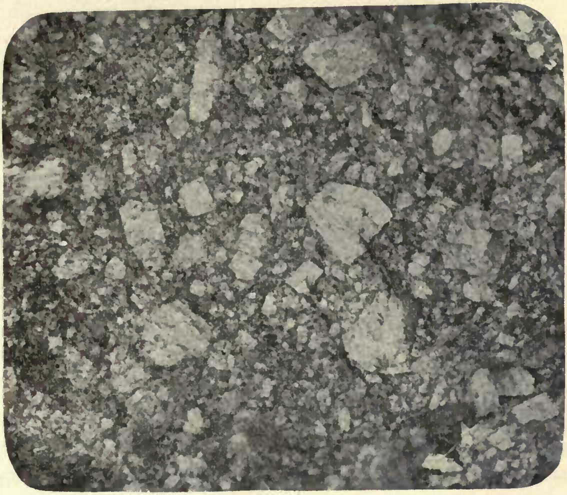
Porphyritic Texture. Porphyry. In this texture, when typically developed, there is a sharp contrast between larger crystals with definite crystallographic bounding faces, which are termed *phenocrysts* (Greek, *φαίνειν*, to show), and the material in which they lie embedded, called the *groundmass*. This groundmass may have the textural characters described on a preceding page, it may be even-granular, coarse or fine, it may be dense or wholly or partly glassy. A rock with this textural fabric is called a *porphyry*.* Examples are shown in Plate 7.

Great variations are seen in the phenocrysts; they may be extremely numerous and the amount of groundmass small or the reverse; they may be an inch or more in diameter or they may be so small as to require close observation to detect them; they may be of light-colored feldspars and quartz or dark-colored ferromagnesian minerals, hornblende, augite and pyroxene, or of both kinds of minerals. Again, they may be extremely well crystallized and afford such striking specimens of perfect crystal development that they find a place in mineral cabinets or they may be very poorly defined in crystal form. And with increase in numbers and poor crystal form, all degrees of transition into the even-granular texture may be found. The porphyritic texture is extremely common in lavas and in intrusives of small mass such as dikes, sheets and laccoliths; it is rarer in

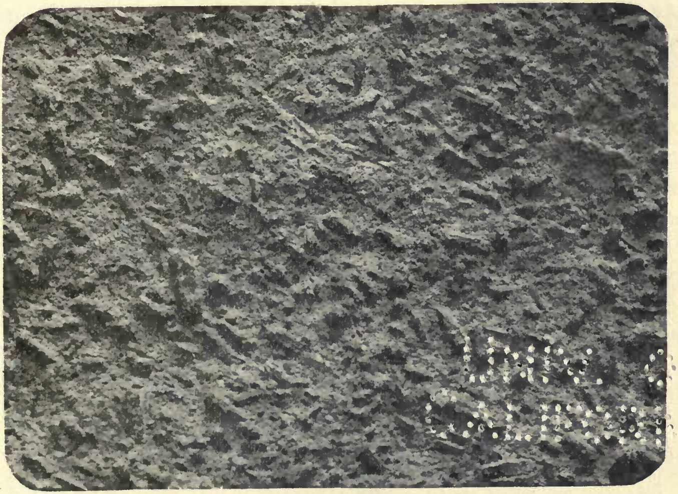
---

* The porphyritic texture is not a contrast of *colors* of mineral grains but of *sizes*. Care must be taken, therefore, not to confuse, for instance, a white rock consisting of grains of light-colored minerals such as feldspar, in which are embedded a few conspicuous black grains of a ferromagnesian mineral of the same size, such as hornblende, with a porphyry.

PLATE 7.



A. With Phenocrysts of Feldspar.



B. With Phenocrysts of Augite.

PORPHYRY TEXTURE.

the abyssal rocks, but is sometimes seen, especially in granites.

Origin of Porphyritic Texture. In the case of many effusive rocks or lavas it is easy to understand why they have a porphyritic texture. The lavas of many volcanoes, as they issue to the outer air, are full of growing crystals, often of considerable size, suspended in the molten fluid. The latter, however, subjected to new conditions, is forced to cool rapidly and assumes a fine-grained, or dense crystalline, or even a glassy, solid condition with these larger crystals embedded in it, and thus the completed rock has a porphyritic fabric. The same process may serve to explain this texture in some of the smaller intrusives, such as dikes and sheets, but it cannot serve as a general explanation for all cases because in some dikes, laccoliths, etc., there is good evidence that the phenocrysts have not been brought thither but have formed, like the rest of the rock, in the place where we now find them. It also fails to explain the porphyritic border of many granites and the large phenocrysts found in other granites; nor does it explain the origin of the phenocrysts themselves, why a few large crystals have formed while the rest of the magma fails to crystallize. Evidently some more general explanation is needed.

It has been previously shown that molten magmas must be considered as strong or saturated solutions of some compounds in others. As the mass cools down it may become supersaturated. Now it has been shown that some saturated solutions cannot crystallize spontaneously but require to be inoculated with a minute fragment of the substance in solution; this is called the *metastable* state. Other saturated or supersaturated solutions either crystallize spontaneously or can be induced to do so by shaking or stirring with a foreign substance.

Miers has shown that the same solution may pass from one to the other of these states in accordance with changes of temperature, and suggests that a magma may be in the metastable condition in which a relatively few crystals induced by inoculation from the surrounding rocks are growing as phenocrysts and by cooling pass into the labile condition when spontaneous crystallization of the remaining liquid will ensue and form the groundmass. Or it may start in the labile condition when the formation of a crop of phenocrysts will reduce it to the metastable state, in which condition it may be erupted as a lava, or remaining and cooling down it may pass into a new labile state, thereupon crystallize and form the groundmass. The recognition of these states in cooling saturated solutions (and we must regard the molten magmas as such) seems quite sufficient to explain the different variations of porphyritic texture which occur.

Some Structures of Igneous Rocks.

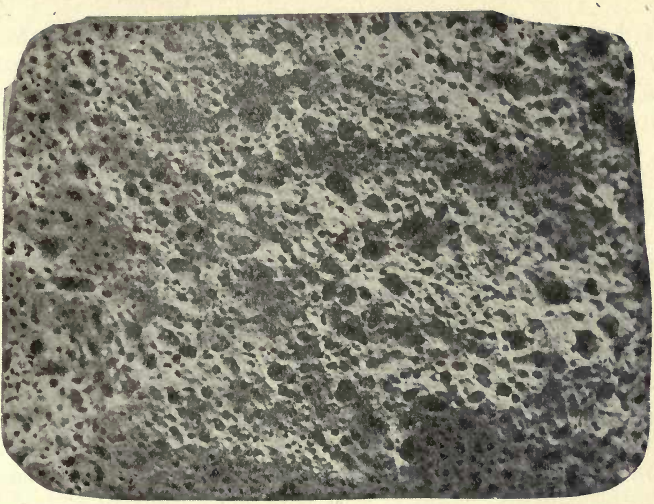
The word *texture* is reserved for those appearances of the rocks which are occasioned by the size, shape, color, etc., of the component crystal grains. Certain larger features exhibited by the rocks may be classed under the term of *structure* and will now be described.*

Vesicular Structures. When a molten magma rises to the surface and especially if it issues in the form of lava, the pressure upon it is relieved and the water and other vapors it may contain are given off. This has a tendency, if it is still soft and stiffening, to puff it up into spongy vesicular forms as illustrated in Plate 8. In the case of very siliceous lavas it may be entirely changed into a light glass froth called *pumice.* Such forms are especially produced in the lava in the throat of a volcano, where the issue of gases is rapid or in the top portion of a flow. Except in a rare and very limited way on the sides

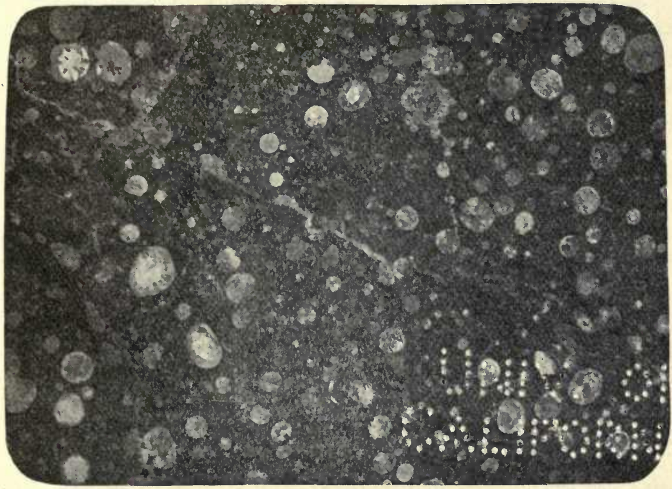
---

* An example of the difference between the two usages would be this. A certain lava from flowage might appear in layers; the layers are of rock composed of exceedingly fine particles. We would say then that the lava had a banded structure and a very fine compact texture.

PLATE 8.



A. VESICULAR LAVA.



UNIV. OF CALIFORNIA

B. AMYGDALOIDAL BASALT.

of dikes they never occur in intrusive rocks, and the presence of well-marked vesicular structure may be taken as pretty sure evidence that the rock exhibiting it was originally a surface lava. In the throat of a volcano such spongy forms of lava may, by explosions of steam, be driven in fragments into the air to fall as dust, ashes, lapilli, etc., making volcanic tuffs and breccias as described elsewhere.

Amygdaloidal Structure. Amygdaloid. When a lava has been rendered spongy (vesicular, as described above), it may be permeated by heated waters carrying material in solution which may be deposited as minerals in the cavities. This happens especially in basaltic lavas, and the dark rock then appears filled with round or ovoid whitish bodies which from a fancied resemblance to the kernel of a nut are termed *amygdules,* from the Greek word for the almond. The structure is called the *amygdaloidal* and a rock exhibiting it is often termed an amygdaloid. It is shown in Plate 8. While the smaller cavities are usually filled solid, the larger ones are often hollow, the minerals projecting in crystals from the walls as in geodes, and from such amygdaloidal cavities some of the most beautiful crystallizations are obtained. The minerals most frequently occurring are quartz, which is sometimes of the amethyst variety, calcite and particularly zeolites. The basaltic lavas are an especial home of these latter minerals, some of the more common kinds being analcite, stilbite, natrolite, heulandite and chabazite. The basalts of India, Iceland, Scotland, Nova Scotia and other localities have furnished specimens which are known in all mineral collections.

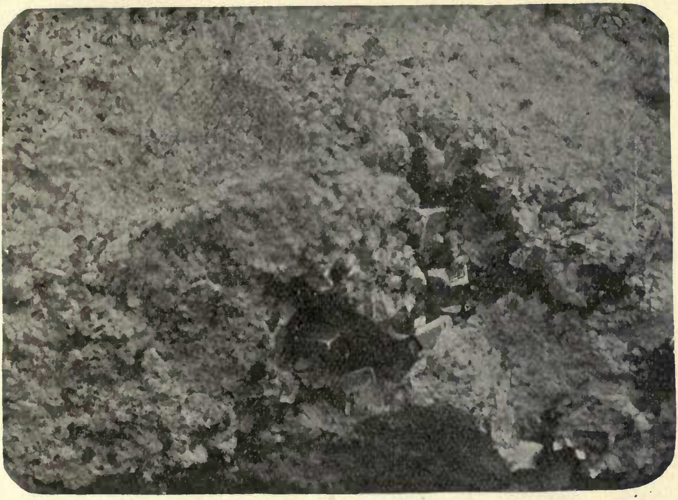
This structure is most commonly and typically developed in surface lavas, that is, in effusive rocks, but it is also seen at times in intrusive rocks, such as dikes and sheets, especially at their margins.

Miarolitic Structure and Porosity. The volume which a magma occupies in the molten condition is considerably greater than that which it has when changed to a solid crystalline rock. It is probably greater in the liquid state than when cooled to a glass but how much we do not know. This contraction in volume, in passing into the crystalline state, is accompanied by a corresponding rise in specific gravity. Thus an obsidian glass, consisting chiefly of high silica with moderate amounts of alkalies and alumina, has an average specific gravity of about 2.2–2.3, but the same material crystallized into a quartz-feldspar rock (granite) has a specific gravity of 2.6–2.7. There would be a corresponding reduction in volume.

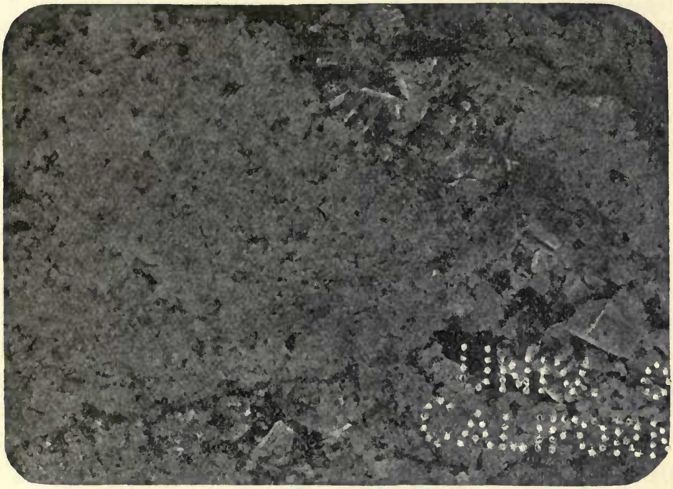
In general this contraction of volume, during the process of crystallizing, produces minute interspaces or pores between the mineral grains, and cracking and jointing of the mass, a process described in the following section. This production of pores accounts for the capacity of the rocks to absorb moisture. It appears to be greatest in the coarse-textured rocks, much less in the finer-grained ones; greater in granites, less in diorites and other ferromagnesian rocks. In the case of porous vesicular lavas the amount of pore space may be very great, but in ordinary crystalline igneous rocks it is small, usually less than one per cent of the rock volume.

In some cases, however, there may be distinct cavities produced. These are commonly very small, sometimes an inch or so in diameter and in rare instances as much as several feet. It often happens that the crystal components of the rock on the boundary walls of the cavity are much larger in size than the average grain, and project into it, bounded by distinct faces and of good crystal form. One notices also, especially in granites, that the quartz and feldspar crystals are often accompanied by those of muscovite, topaz, tourmaline and others which are foreign to the general mass of the rock but are common in pegmatite veins. These are also well crystallized. The presence of the water vapor, fluorine, boron, etc., necessary for their production, as well as the larger size and

PLATE 9.



A. MIAROLITIC CAVITY.



B. MIAROLITIC CAVITIES PASSING INTO PEGMATITE.

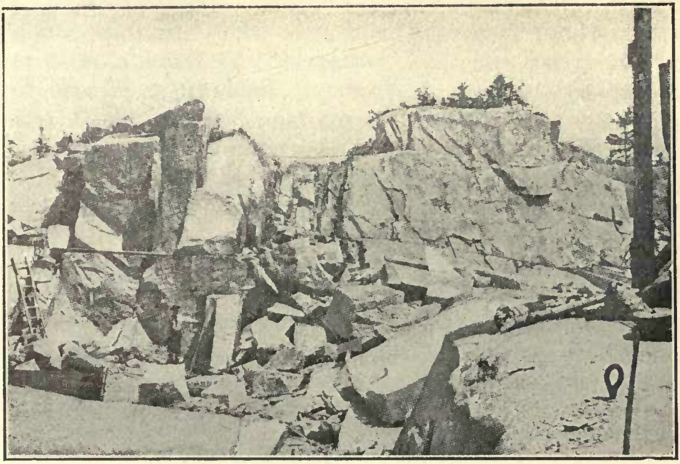
distinct form of the crystals, shows that such mineralizers, excluded elsewhere from the magma during the process of crystallization, collected in these cavities, possibly helped to enlarge them, and promoted the formation of the unusual minerals and the good crystal forms which they and the ordinary rock minerals exhibit. Such hollow spaces are called *miarolitic cavities* and a rock which contains them is said to have *miarolitic structure,* from a local Italian name (*miarolo*) for the Baveno granite which shows it. Such drusy cavities are distinguished from geodes and others, in which the minerals have been deposited from solutions, by the fact that they have no distinct wall separating the minerals from the containing rock. They often furnish fine mineral specimens. An example of one is seen in Plate 9.

Jointing of Igneous Rocks. The most important way in which the contraction of a body of magma, after cooling and crystallizing into rock, manifests itself is in the production of *joints.* These are the cracks or fissures which, running in various directions, divide the mass into blocks, fitted together like masonry and usually according to more or less definite systems. Sometimes this shows itself in the formation of rudely cubic or rhomboidal blocks, as shown in granites and other abyssal rocks, sometimes in a platy parting which may be quite thin and cause the rock mass at first glance to resemble sedimentary beds, and sometimes in concentric or spheroidal forms which develop rounded or ovoid bodies like melons as the weathering and rock decay progresses. Platy and spheroidal partings, and jointing on a small scale by which the rock body is divided into little blocks, are most common in small intrusions — in dikes, sheets, etc. — and in surface lavas. Such jointing is a matter of great geologic importance in permitting the entrance of air and water to act in the weathering and decay of rocks and in the processes of erosion, especially the splitting and breaking of them by the action of frost. As can be readily inferred it is also of great practical importance in the work of rock excavation, in mining operations and in quarrying. (See Plate 10.) Were it not for such joints almost every igneous rock mass would furnish suitable material for quarrying, whereas on the contrary it is difficult to find a granite jointed on so large a scale that it will furnish solid blocks, for example, like those from which the celebrated Egyptian obelisks were made.

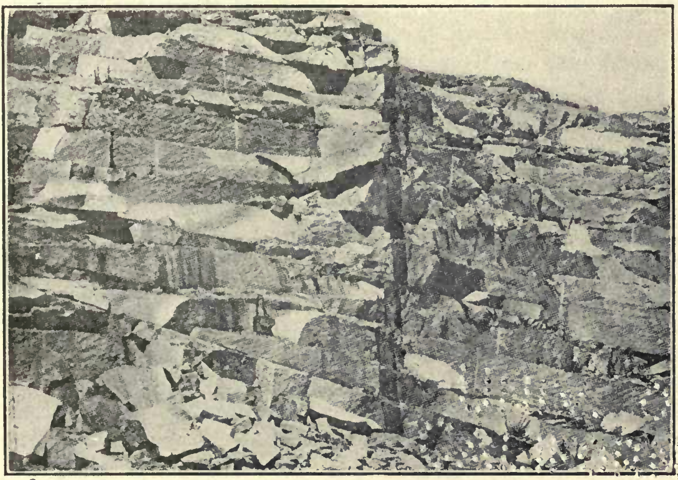
Columnar Structure. The most remarkable way in which the jointing of a cooling mass of igneous rock, explained above, manifests itself is in the production of columnar structure. This is found both in intrusive and extrusive occurrences and in all kinds of igneous rocks, but is usually best displayed in basalts. The whole mass is made up of columns, regularly fitted together, from a few inches to several feet in diameter and from one foot to two hundred feet or even more in length. An example is shown in Plate 11. The celebrated Giant's Causeway on the north coast of Ireland is one of the best known examples of this. In the most perfect cases, as in the one just mentioned, the cross sections of the columns are regular hexagons and the columns are divided lengthwise at regular intervals by cross joints whose upper surfaces are shallow cup-shaped. The columns are always perpendicular to the greatest extension or main cooling surface of the igneous mass, hence in a lava flow or intrusive sheet they are vertical — assuming the flow or sheet to be horizontal — while in a dike they tend to be horizontal. Such a dike when exposed by erosion tends to resemble a stretch of cord-wood regularly piled.

The cause of this structure seems to be as follows. When a homogeneous mass is cooling slowly and regularly, centers of cracking tend to occur on the cooling surfaces at equally spaced intervals. From each central interspace three cracks radiate outward at angles of 120 degrees from each other. These intersecting produce regular hexagons and the cracks penetrating downward

PLATE 10.



A. High Isle Quarry, Maine.



B. Allen Quarry, Mount Desert, Maine.

JOINTING IN GRANITE AND ITS USE IN QUARRYING.

(U. S. Geological Survey.)

make columns. This regular arrangement produces the greatest amount of contraction with the least amount of cracking, provided the centers are equally spaced. But as the contractional centers are not always equally spaced, three, four, five and even seven-sided columns occur. The columns again, contracting lengthwise, break into sections as they form. The same principle is also seen in drying mud-flats which crack into polygonal shapes and in the prisms of drying and contracting starch. Such columns, however regular their appearance, are not crystals but pieces of rock and should not be confused with the hexagonal prisms produced by the crystallization of certain minerals, such as quartz, beryl, etc., which are due to an entirely different process.

Inclusions in Igneous Rocks.

Not infrequently there may be noticed in igneous rocks masses which differ in mineral composition, color and texture from the rock which includes them. They may vary in size from a fraction of an inch to several yards across. Study of them shows that sometimes they present all the characters of distinct kinds of rock and by these, and by their angular shapes, they show clearly that they are fragments of pre-existent rocks which the magma on its way upward has torn loose from the walls of its conduit and brought along, or blocks from the roof or sides of the chamber, in which the magma came to rest, which were loosened and sank into it. They may be composed of other kinds of igneous rocks or of sedimentary ones, such as shales, limestones, etc. In the former case they are not usually much changed, but the fragments of stratified rocks generally exhibit the results of intense metamorphic action, such as described elsewhere, and are much altered. In large intrusive masses inclusions of this character are most apt to occur near the border. An inclusion in granite is shown in Fig. 1, Plate 12.

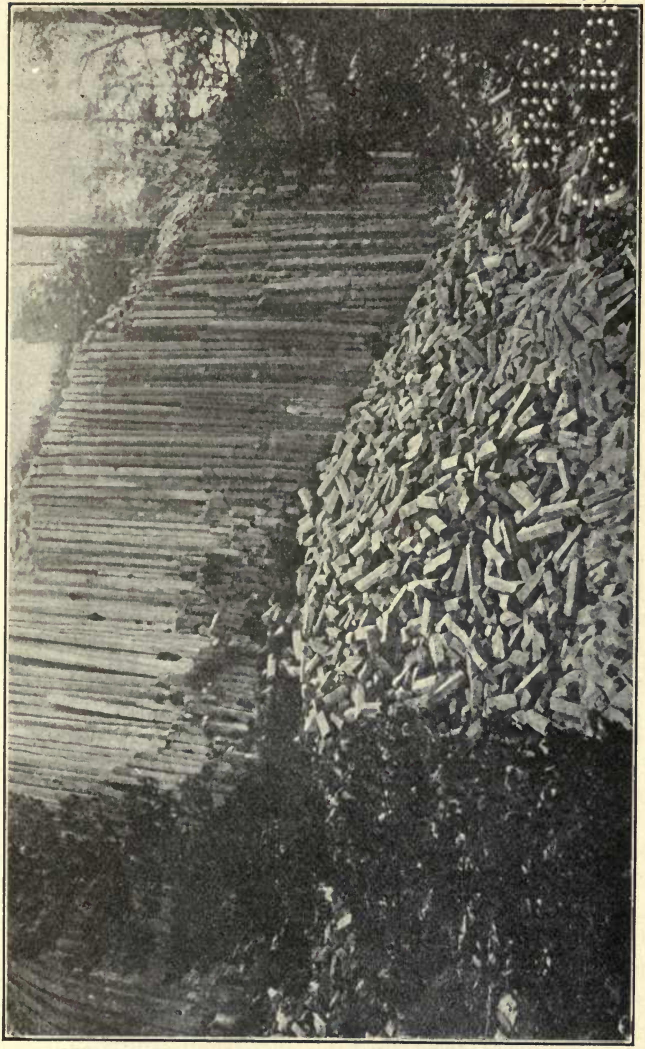
In other cases the inclusions are composed of certain minerals, especially the ferromagnesian ones, which occur in the rocks and which by some process have been aggregated into lumps, such as the masses of olivine crystals often found in basalts. It is clear that such aggregation or growth of these minerals must have taken place while the remainder of the rock was still in a liquid condition. They have been termed *segregations.*

In still another kind the inclusions are indefinite in form and often of boundary; they are apt to be drawn out, lenticular, streaky in character and they may consist of the same minerals as the main mass of the rock but in quite different proportions, or they may contain different minerals. Thus one sees streaks in granite which may be much richer in hornblende or biotite than the enclosing rock. Some have held that these are due to inclusions of other rocks which have been melted up and then recrystallized and in some cases they may have had this origin, but for the most part they are regarded by the majority of petrographers as caused by streaks and spots in the original magma of a different chemical composition from the main portion. The cause of such nonhomogeneousness in the magma is ascribed to differentiation, as discussed elsewhere in this volume. Such streaky portions are called by the Germans *schlieren* and in default of anything better this word is often used for them in English.

Sometimes lavas show a streaky or even well banded structure, portions differing from one another in composition or in texture having been drawn out in the flowage. This is known as the *eutaxitic* structure.

Origin of Igneous Rocks — Differentiation.

The fact that lavas differing decidedly from each other in mineral and consequently in chemical composition have been erupted by the same volcano at different periods, early attracted the attention of geologists and led to much speculation as to its cause. Thus felsites and



COLUMNAR STRUCTURE IN LAVA, SAN JOAQUIN RIVER, CALIFORNIA.

(U. S. Geological Survey.)

basalts have both been frequently noticed as the products of eruption from a single vent. One explanation, which used to be advanced, was that within the earth there were two layers of magma, an upper one rich in silica, alumina and alkalies, the other and lower, poor in silica but rich in iron and magnesia; accordingly as the eruption came from one or the other of these, felsites or basalts were produced, while their mixtures gave rise to intermediate products. It was soon seen, however, both on chemical and geological grounds, that this view was insufficient to explain the origin of all igneous rocks.

As the study of rocks progressed, other facts of a similar nature came to light. Thus in the single rock mass composing the core or neck of an old volcano,* where the magma cooled under conditions favorable for the production of the even-granular or granitic texture, it is not infrequent to find that it is composed of two or more distinct kinds of rock. The boundary between these will sometimes show that one was erupted after the other had solidified in its place, since fragments of the latter are enclosed in the former. This is of course merely carrying deeper down into the volcanic conduit the same facts shown by the surface lavas previously mentioned. Other cases, however, are of a different nature and of such geological importance that they demand separate consideration.

Border Zones. In recent years the study of deep-seated intrusive masses, such as stocks of granite, syenite, etc., which have become exposed by long continued erosion, has shown that not uncommonly such masses have an outer border or mantle of rock which differs in mineral composition from the mass which it enfolds. The thickness of such a border zone is very variable, even in the same mass, and in places it may be lacking; it may be several thousand feet thick or only a few hundred or even less. While in general it bears some proportion to the

---

* See volcanic necks, page 138.

general size of the whole mass there is no rule about this which can be stated.

In most cases this zone or *border facies,* as it is sometimes called, is produced by an enrichment of the rock in the ferromagnesian minerals, such as pyroxene, hornblende, biotite and iron ore. Generally the enriching minerals are the same as those more sparsely distributed in the main rock body but very often different ones are observed among them. From this it is clear that chemically the border zone is richer in iron and magnesia, and to some extent in lime, than the main mass, with a corresponding diminishing of silica, alumina and alkalies. Since they contain less of silica, the acid oxide, they are commonly called *basic* zones. Not all border zones, however, are basic ones; a number of instances are known where the margin of the intrusion is poorer in lime, iron and magnesia and consequently in ferromagnesian minerals than the interior rock body and therefore contains more silica, alumina and alkalies, which expresses itself mineralogically in greater abundance of feldspar and sometimes of this and quartz. In this case they are called *acid* border zones. Thus on the one hand intrusions of syenite have been found which pass into pyroxenite at the border while on the other hand syenite intrusions are known which become granite towards the margin. It must not be imagined that there is anything approaching a contact between the two kinds of rock. The one kind passes gradually into the other without change in texture and all the facts indicate that this arrangement was not produced by successive intrusions of different magmas but by some process in a single body of magma after it had entered into its chamber.

Zoned Laccoliths. The zonal arrangement just mentioned is still more strikingly shown in the case of certain laccoliths which have been found in Montana and elsewhere. Where these have been laid bare and dissected by erosion the study of them shows that they consist of a body of rock of one kind, generally one consisting mostly of pyroxene, enclosing within a core of rock of a totally different kind, usually a syenite, which is of course chiefly feldspar. A cross section through such a laccolith is shown in the accompanying diagram, Fig. 70.

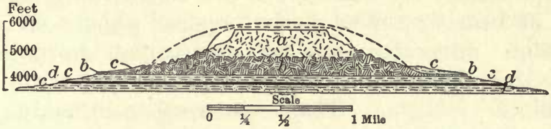


Fig. 70. Diagram of a Zoned Laccolith: *a*, feldspar rock; *b*, pyroxene rock; *c*, shales and sandstone; *d*, underlying sheet of intrusive basalt. Figures in feet are heights above sea-level.

That the pyroxenic rock once had the extension shown by the restoration in the figure is known from other examples in the neighborhood where the erosion has not been so great, and it is still found above, enwrapping the interior syenite.

Associated Complementary Dikes. Another phenomenon, of the same category as those just described, is seen in the dikes so commonly found associated with larger intrusive bodies, such as stocks of granite, syenite, diorite, etc., where these have become exposed by dissective erosion. They are in origin subsequent to the main mass which they accompany and are found cutting it and also the surrounding rocks. In the latter, these minor intrusions may appear, not only in the form of dikes, but also in intrusive sheets, laccoliths, etc. These rocks are divisible into two classes; in the first they are very poor or entirely wanting in ferromagnesian minerals (salic rocks) and have been called *aplitic* dikes, since the dikes of aplite usually found associated with granites are the most common and best known representatives of this class. They have also been called *leucocratic* dikes (from the Greek, prevailing white) in allusion to their general light color, due to the fact that they are mostly composed of feldspars or of these with quartz. They are generally fine-grained rocks, sometimes of a sugar granular texture, sometimes dense and to be classed as felsites. In some cases they are porphyritic. They usually occur in narrow dikes, a few feet wide and sometimes only an inch or even less in breadth.

In the second class the rocks are heavy, dark or even black, of basaltic aspect and composed chiefly of ferromagnesian minerals, iron ore, pyroxene, hornblende, biotite and olivine, in variable amounts and with very subordinate feldspar. They are very commonly porphyritic with good-sized phenocrysts of the minerals mentioned above in a dense dark groundmass, though these are often wanting. Such rocks have been called *lamprophyres* (from the Greek, meaning glistening porphyry in allusion to the biotite), and are termed *melanocratic* rocks (μελανός, black). In our field classification they would be named biotite melaphyre (or mica trap), hornblende melaphyre, etc., according to the prevailing phenocrysts. They also usually occur in narrow dikes and are more apt to cut the surrounding rocks than the main intrusive body they accompany, thus reversing the custom of the aplites.

These two kinds of rocks, the aplitic, light-colored feldspathic, and the lamprophyric, dark-colored, with ferromagnesian minerals, are termed *complementary* because taken together they represent the composition of the main masses they accompany. If we could mix them in amounts proportional to the bulk of their occurrence we should obtain a rock whose chemical (and largely mineral) composition would be that of these larger masses upon which they appear to depend as satellite bodies. In some cases this has been actually tested and proved. When all the facts concerning their mode of occurrence are taken into account they appear to have been formed by secondary, later intrusions of the same magma producing the larger stocks, which in some way has divided into two unlike sub-magmas. If they should break through to the surface they would give rise to lava flows also unlike, to felsites and basalts, and thus explain in part the phenomena noticed in many volcanoes.

It is to be understood of course that not all dikes, sheets and laccoliths belong in this category of complementary rocks. On the contrary we very often find that the same magma which produces stocks, necks, etc., occurs in intrusions of this character. They then have the same minerals and composition as the larger masses, or if independent bodies they usually contain both ferromagnesian and feldspathic minerals in due amounts. Only, as explained on page 153, they are liable to differ in texture from the stocks and are very apt to be porphyries. Dikes, etc., of this kind have been called *aschistic*, which means undivided, while the complementary aplites and lamprophyres have been termed *diaschistic*, which means divided, in allusion to their dual nature.

Differentiation. The varied lavas of volcanoes, the marginal zones of stocks and necks, the zoned laccoliths and the associated complementary rocks, which have been described in foregoing sections, as well as other similar features, present to us a body of geological facts that can only be satisfactorily explained by the assumption that in some way magmas, which form igneous rocks, have the capacity of separating into sub-magmas, unlike the original, but which, if mixed in proper proportions to a homogeneous whole, would again reproduce it. Regarding the division there seems to be in general two opposite poles toward which the sub-magmas tend; to one concentrate the iron, magnesia and to a large extent the lime, to the other the alkalies, alumina and to a great extent the silica. The one gives us ferromagnesian rocks such as gabbro, the other feldspathic rocks such as granite. While this is so in general, we find in detail the process infinitely varied in nature; thus in some places one may observe a division among the alkalies, an enrichment of potash towards one pole as compared with soda or vice versa.

If the body of magma has come to rest in its chamber and this process of differentiation takes place and it then, crystallizing, solidifies and forms rock, it is evident that such a rock body will be unlike in its different parts, and marginal zones, zoned laccoliths, etc., will be produced; or if further movements occur, producing new intrusions or these with extrusions, then associated complementary dikes, sheets and lava flows may occur.

This division into sub-magmas is termed the *differentiation of igneous magmas* and the reality of it as a process seems well established on geological grounds by a large body of facts. That in some manner such a process takes place and on the other hand the understanding of how and why it does take place, are two entirely different affairs, and while every one who is thoroughly conversant with the facts is obliged to admit the former, a wide diversity of views, owing to insufficient knowledge, prevails in regard to the latter. Some phases of this subject are discussed in the following paragraphs.

Formation of Zones and Ore Bodies. One partial explanation that has been offered for the zoned structures previously mentioned is of importance because it affords at the same time an understanding of the origin of a certain class of ore bodies which in some places are of considerable extent and value. On page 148 it was shown that there was a general order of crystallization of rock minerals beginning with the iron ores, then passing into the ferromagnesian silicates and finishing with the feldspars and quartz. In an enclosed body of magma, crystallization would generally begin when the temperature had fallen to the proper degree. This would naturally first occur at the outer walls where the effect of cooling is felt. Against these the iron ores and ferromagnesian minerals, the earliest to crystallize, would form and, if the process were extremely gradual, slow convection currents in the magma would bring fresh supplies of material to crystallize there until large amounts of these minerals had formed. This might go on until the temperature had fallen to a point where the main body of magma was compelled to solidify and the rock mass as a whole produced. The outer margin would be much enriched in the earlier formed minerals, giving a zoned arrangement to the whole mass. In such places at the margin the iron ores are sometimes so locally concentrated as to yield workable deposits of value, though very commonly the ore is titaniferous and therefore cannot be used commercially. The same explanation has been offered for the occurrence of sulphide ores of iron containing copper and nickel, of corundum and of other useful minerals found in similar situations.

Origin of Salic Border Zones. The explanation given above would show how marginal zones richer in ferromagnesian minerals might arise but it has been observed that masses of granitic and syenitic rock are sometimes poorer or deprived of these minerals at the margin of the mass while the main part contains them in considerable amounts, thus making salic zones. An explanation which has been offered for this is as follows: If a solution of a salt in a liquid (such as sea-water) be cooled down until it is forced to crystallize (freeze) it is found that the substance in greatest excess, salt or liquid, will solidify first until a certain definite proportion of dissolved salt and liquid are obtained, called the *eutectic* mixture, when both remaining salt and liquid will crystallize simultaneously and the whole mass become solid. The proportion of salt to fluid, forming the eutectic, varies with the kind of salt and of solvent. Thus when sea water freezes the ice first formed contains no salt, the latter forming in the remaining water a brine of increasing strength until the eutectic point is reached, when both solidify together. In the case of granite and syenite the oxides composing the quartz and feldspars are present in great excess and may be considered the solvent for the others. It is possible that under proper conditions these might solidify at the outer margin, the other oxides, those of iron, magnesia, etc., concentrating in the remaining portion and tending to make an eutectic mixture. Thus when the whole solidifies the inner part will contain ferromagnesian minerals, and the outer part will be poor or wanting in them. In the case of many diorites and gabbros, where the oxides of iron and magnesia are in great excess, they would be the solvent, and we should expect border zones of ferromagnesian minerals. It is evident this explanation, and the one previously given, which depends on the order of crystallization, in the case of highly feldspathic rocks, are opposed to each other; the first tends to make ferromagnesian zones around granite and syenite, the latter salic ones. In the diorites and gabbros both tend to produce margins richer in ferromagnesian minerals.

Zones by Absorption. It has also been suggested that such zones are produced by the magma melting its containing walls and thus, by absorbing foreign material, becoming in composition, at its border, unlike the main mass. Being thus unlike it would naturally have a different mineral composition on solidification. It is possible that this may have happened in some cases but it cannot serve as a general explanation because in many cases we find the border of an entirely different mineral (and chemical) composition from that which it ought to have if the rocks with which it came in contact had been melted and absorbed.

General Explanation. It is obvious that the hypotheses discussed above, while they may serve to explain border zones and marginal ore deposits, do not give a general explanation for the differentiation of igneous rocks. For the occurrence of complementary dikes, of different lavas from the same volcano, and the mixtures of different types, which are not marginal, in the same stock, as well as other facts, show clearly, that in general, differentiation is not a division by a process of solidification, but one which occurs in a magma in such a manner as to produce separate bodies of differing *liquids* which may be independently ejected or intruded. It must occur before there is any solidification. While we see that this is so, both from geological and chemical facts, no general explanation, which is in all respects satisfactory, has been offered for this process. Different hypotheses, which it would be beyond the limits of this work to state and discuss, have been suggested by various authorities, but our knowledge of the physical chemistry of molten magmas is yet too limited to know their proper value and applicability. It is probable the processes of differentiation are quite complex and that they are produced by a variety of factors, the laws governing which must all be taken into account in any general explanation. It is known that molten artificial glasses and molten alloys of metals, under conditions not yet well known, do not remain homogeneous but undergo a kind of differentiation, and it is along this line of experimental research that light must be sought to explain the facts as we find them in Nature.

Petrographical Provinces. Consanguinity. It has been noticed in the study of rocks, that those belonging to certain regions have particular features which to a greater or less degree are found to be distinctive of all the members of the group which occur there. This is shown, sometimes in the presence of particular varieties of minerals, sometimes in peculiar textures, sometimes in peculiarities of chemical composition and usually in a combination of these things. They may be shown in varying degrees by all the different rocks of the region: thus, for example, by syenites which are chiefly composed of feldspar and by dolerites in which ferromagnesian minerals prevail; in intrusive stocks of granular rocks with their associated complementary dikes and sheets and in lava flows of felsites and basalts. These common characters are sometimes strongly marked and at other times only to be seen by the experienced observer. The fact that such distinguishing features occur in the different types of a certain region and serve to indicate their relationship to one another and to show a common origin by differentiation is termed the *consanguinity* of igneous rocks, and that region over which the rocks thus show genetic relations is called a *petrographic province,* or *comagmatic* region. Thus the comagmatic region of South Norway is characterized by the extremely high percentage of soda in the magmas, which gives rise to certain minerals and peculiar rock textures; those of Italy and central Montana by very high potash which shows itself in the formation of the mineral leucite, common in such regions but rare or unknown elsewhere; that of the western Mediterranean islands and eastern Spain by an abnormally high amount of titanic oxide in its rocks.

Such evidences of consanguinity in rock groups and the proofs which they furnish of comagmatic regions cannot usually be observed in field work and in the megascopic study and determination of rocks. They generally demand careful and complete investigation of thin sections under the microscope, aided by chemical analyses in the laboratory, together with a broad acquaintance of the literature of this subject, in order to be perceived and appreciated. The matter, however, is one of great interest and although one may not be either a chemist or petrographer, he may yet appreciate the significance of its bearing on the solution of problems of the greatest importance in geology. It is evident that before we can safely theorize as to the origin and history of the earth we must first know the nature of its component parts and the laws governing their distribution.

Post-intrusive Processes.

When a body of molten magma has come to rest in the chamber it is destined to thenceforth occupy as a solidified rock mass, cooling and eventually crystallization begin. From this point on, so far as the magma is concerned, those factors are at work which have been described elsewhere, and which in time will produce the completed rock. During this period of crystallization the volatile substances dissolved in the magma and previously contained under pressure, such as fluorine, boric acid, carbon dioxide and especially and chiefly water, which have been already described as *mineralizers*, are gradually excluded, except in so far as they may take part in the chemical composition of some of the minerals.

This period in the history of the formation of a rock body, when it is solidifying and giving off, as it crystallizes, heat and vapors, is called the *pneumatolytic* (Greek, gas, and to loosen), and these agents generate important results. At the surface they give rise to hot springs, fumaroles, solfataras, and similar secondary igneous phenomena; in the depths they produce in the rocks surrounding the igneous mass a variety of features known under the term of *contact metamorphism*, and in the already solidified parts of the igneous mass they bring about the formation of *pegmatite dikes*, of *greisen* (described under Granite) and in some cases of *ore deposits;* things which are treated in the following sections.

Pegmatite Dikes or Veins. It has been previously stated that when deeply formed stocks or masses of granite, syenite, diorite, etc., have been laid bare by erosion they are very frequently found to be cut by complementary dikes of felsitic and basaltic aspect. In addition it is also frequently observed that they are penetrated by dikes which display certain definite characters, the most marked of which is the very large and sometimes enormous size of the individual minerals composing them. Such dikes have been termed *pegmatite* dikes, from the name given by Hauy to the intergrown masses of quartz and feldspar found in them when they occur in granites. Dikes of this character not only cut the stocks and batholiths, to whose intrusion they owe their origin, but are also found penetrating, as offshoots, the rock masses enveloping them. There are a number of features which particularly characterize them, as follows:

a. They consist in large part of the ordinary minerals which compose the rock to which they belong, but these, instead of having their regular order of successive crystallization, show by their interpenetration that they have crystallized more nearly if not entirely, simultaneously.* The size of the individual crystals is a character that has been mentioned. Feldspar and quartz may occur in crystals a foot or even several feet long, apatite in dimensions like the handle of a broom, mica in crystals yielding plates a foot or more in diameter and other minerals in similar proportions. It is not to be understood that these sizes represent the average; they are the extremes which are, however, not infrequently attained. Moreover, the essence of pegmatite structure does not lie in mere size, for many rocks are very coarse-grained which are not pegmatites, but rather in the other qualities enumerated.

b. Another peculiar feature is that in many pegmatites there is an obvious tendency for the minerals to grow outward from the walls of the dike on either side and project inward toward the center. This may become very marked and there may even be an empty space at the center into which the minerals project showing crystal faces as in miarolitic cavities (page 159) or in the vuggs of mineral veins. The whole effect is to produce in a rough way a zoned, banded or ribbon structure, which is often so perfectly seen in mineral veins.

c. Another character is the extreme variability in the relative proportions of the component minerals from place to place, a variability not seen in the main rock mass. Thus in granite pegmatites traced along the outcrop of the dike great variations in the relative amount of quartz and feldspar may often be observed; in tracing

---

* See in connection with this the description of graphic granite in the granite pegmatite veins, p. 212.

them outward from the parent mass into the enclosing rocks they may even pass into pure quartz veins. In other cases they may turn into fine-grained granite (aplite) or felsite, and this change in the character of the dike may occur quite suddenly.

d. They are very apt to contain accessory minerals which are either not found at all in the main rock mass or which microscopic examination shows are sparingly distributed in very minute crystals. These minerals may be divided into two classes. In the one their chemical composition shows that they consist of the ordinary oxides which compose the magmas, alumina, lime, iron, soda, etc., plus the volatile elements or oxides which form the mineralizing vapors. Common ones are tourmaline, which shows the presence of boric acid; topaz and fluorite, which demonstrate that fluorine was present and many, of which muscovite mica is perhaps the most prominent, which prove the important rôle played by water vapor. The other class are characterized by their containing in larger or smaller amounts the oxides of rare elements, such as lithium, caesium, beryllium, molybdenum, cerium, lanthanum, niobium, etc., elements which are detectible with difficulty as minute traces or not at all in the main rock mass. In combination with silica, titanic oxide, phosphoric acid, zirconia, carbonic acid, fluorine, etc., they give rise to a whole host of mineral combinations, too numerous to mention, but of which beryl and spodumene may be cited as examples. No sharp distinction can be drawn between these two classes; many minerals might be placed in either, but definite types of both, like those mentioned, can readily be found.

These accessory minerals often occur also in crystals of great size and sometimes aggregated together in places in the dikes in very large amounts. It is due to this great variety of minerals and the frequent size and perfection of the crystals that the pegmatite dikes are mineralogically of great interest and are, therefore, a favorite hunting ground of mineral collectors. It is to be noted also that each variety of magma (or rock) is characterized by special mineral combinations in its pegmatite dikes, and this applies not only to the ordinary minerals which compose the rocks and distinguish them from one another but also to the accessory ones as well.

Thus the mineral groups found in the pegmatites associated with ordinary granites are quite different from those with the nephelite syenites, as these in turn differ from those of the gabbros.

Origin of the Pegmatites. The simultaneous method of crystallization, the arrangements along the walls of the dike, the variability in the proportions of the component minerals and their frequent huge size all show that conditions, different from those which attended the solidification of the main rock masses, prevailed during the formation of the pegmatites. The presence of hydroxyl, fluorine, boron, etc., also shows that mineralizing agents were abundantly present. Bearing these facts, and those of the geologic mode of occurrence, in mind, we can present to ourselves a view of their origin which would be somewhat as follows:

When a body of igneous magma, such as will form a stock or batholith, comes to rest in place it will commence to cool. This will naturally take place first in the upper and outer portions and here will begin the solidifying of the mass by crystallization. As it becomes solid it breaks up into jointed masses by contraction. The weight of these masses, aided by the rock pressures from above upon the still liquid material below, tends to force the latter upward into the fissures in the solidified part and into those of the surrounding rocks and produce dikes. If differentiation is taking place and there is a concentration of the iron, magnesia and lime towards the outer border, as explained in previous sections, these dikes will be complementary and we will find aplites (and felsites) more commonly in the central mass, and the corresponding basaltic lamprophyres more commonly in the outer portion and in the surrounding rocks.

But as the process of crystallization goes on, the volatile substances in the magma, and especially water in great quantities, beyond what is retained by such minerals as use them in their chemical composition, will be excluded, and more and more as the gases accumulate they must find their way outward. Thus they will tend to force their way upward along the fissures in the solidified parts above and at the sides. These cracks will therefore become channel ways, not only for the still unconsolidated magma as mentioned above (whether differentiated or not), but also for the vapors which will collect in them and in those of the immediately surrounding rock mantle under pressures, which must often be enormous, until eventually they escape. It is evident from this that the ascending magmas in the fissures will at various places become supercharged with these vapors far beyond what obtains in the normal rock. Now, both on experimental grounds and what is observed in nature, it may be regarded as almost certain that no sharp line can be drawn between igneous fusions of silicates (molten silicate magmas) containing water under pressure and hot water solutions. It appears that under pressure water will mix in all proportions with magma so that at one end are molten fusions, at the other hot solutions.*

At 360 degrees water reaches its critical point, that is, heated to this degree, or above, its vapor cannot be turned back into liquid by mere pressure, however great this may be. At this temperature its expansive force is almost 3000 pounds to the square inch, which would require a vertical height of about 2500 feet of granite rock to contain it. Above this temperature sufficient pressures cause it to contract rapidly and it may even occupy less

---

* A good illustration of this is seen in a solution of thallium silver nitrate which boils down, losing water, until a clear molten fluid of the double salt remains which is anhydrous.

volume than it would in the liquid state (see p. 15). The temperatures obtaining in molten rock magmas are far above the critical temperature of water and it must therefore be in the gaseous condition, though under the enormous pressures obtaining under thousands of feet or even several miles vertical of overlying rock, it may well be much denser than water at the surface. Although it has not yet been shown, so far as the writer knows, that water in this state holds substances in solution just as though it were a liquid, we can well imagine that at high temperatures aided by the fluorine and other active substances so commonly with it, its solvent action must be enormously increased, especially its ability to dissolve silica.

Under such conditions it is easy to see that the minerals would crystallize quite differently from those in the normal rock; in some places the magma would be in excess and the results would more nearly approximate those obtaining in the main rock; with diminished water the dike might pass into an ordinary aplite or felsite phase; with increased amounts, in another place, it might pass from the state of a magma into an aqueous solution and here would be favorable conditions for crystallization on a large scale, for growth outward from the walls and for the segregation of the rarer elements. Finally passing onward the solution phase might become more pronounced, only silica would be carried and the dike turn into a quartz vein. Thus, as the degree of differentiation of the magma and the proportion of magma to water vary, we can see how dikes of ordinary rock, of variable pegmatites and quartz veins may be formed, which show in places very clearly their genetic relationships. Also the slow cooling that would occur in great masses of heated rock enclosing the fissure would be favorable for the production of large crystals.

Contact Metamorphism. This term is applied to the changes which are caused by a body of magma coming in contact with other rocks already formed. The word metamorphism, from the Greek, means a change of form or body and is applied to those results, induced by a variety of factors, by which rocks are recrystallized with the formation of new minerals and textures. General or *regional* metamorphism by which rocks are changed over wide areas through various geological agencies is considered in a later chapter; here only the results caused by igneous magmas are treated. In several ways the results of the two are alike and they often merge into one another but in contact metamorphism the extent of the masses involved is, in general, so much less than in regional metamorphism, that from the standpoint of general geology, it is of much less importance. In respect to petrology and to practical field work, however, it is a matter of individual interest and great consequence and it is therefore given separate treatment in this place.

The effects of the contact of a body of magma with other rocks is seen in two ways: in one a change from its general normal character is commonly observed in the igneous rock itself and this is termed the *endomorphic* effect; in the other, changes in the rocks with which it has come in contact are seen and this is called the *exomorphic* effect. We will consider the former one first.

Endomorphic Effects. It has been stated in a previous section that a change in the mineralogical composition of an intrusive rock body is not infrequently observed along the contact, producing a border zone or facies. This is due to a change in the chemical composition of the magma, caused by differentiation, and has been fully discussed. But at times also, even when this process has not occurred, more or less of a change in the minerals of the igneous rock may be seen directly at the contact or as one approaches it. In this case it is due to the presence of mineralizing vapors which, as previously described, tend to be excluded as the mass cools and crystallizes and to escape to the margin and into surrounding rocks.

Through their influence minerals are formed which do not generally occur in the main part of the mass and which are those which have been described as characteristic of the pegmatite dikes. In granites the most characteristic is perhaps tourmaline, whose presence is indicative of boron, hydroxyl and fluorine. It is apt to take the place of the biotite in the main rock and its occurrence as a regular component of the granite should always lead to a suspicion of approach to the contact, though it is also found in the neighborhood of fissures which have served as the conduit for pneumatolytic exhalations.

A variety of the granite of the Black Hills from Harney's Peak illustrates this phase; in addition to the usual quartz and feldspar, the rock contains black tourmaline, abundant and well crystallized muscovite, green beryl and red garnets: such minerals recall the associations seen in pegmatites.

It may even happen that the accumulation of mineralizing vapors is so great at the outer margin before crystallization begins that the conditions are favorable there for the formation of a true pegmatite zone. The writer has observed a granite stock in the White Mountains enwrapped by a mantle of pegmatite; the large plates of muscovite are set perpendicular to the contact and the mixture is much enriched in quartz. Similar examples are known from other localities, and in Pelham, Mass., a pegmatite mantle partly enfolds a mass of peridotite in the gneiss. Phenomena of the character described above are most noticeable about the larger intrusions, such as batholiths, stocks, etc.; in dikes, sheets and minor intrusions they are not so conspicuous or are entirely wanting.

A much more common endomorphic contact effect is a change in *texture* and this is independent of any change in mineral composition, in fact, is largely observed where the mineral composition remains constant. The most usual feature of this kind is a change in the average size of grain in the rock which grows smaller as the contact is approached. The rock indeed may become exceedingly dense at the contact and thus for instance a granite whose average grain is of the size of coarse shot may turn into a compact homogeneous appearing felsite. This is of course due to a more rapid and general crystallization produced by the chilling effect of the contact wall. Instances are even known where the cooling caused by the cold rocks, with which the magma came in contact, was so rapid that solidification took place at the margin before crystallization could begin, with the production of a thin selvage sheet of glass. Such instances are most liable to occur in narrow dikes, in which the cooling of the contiguous rocks is most strongly felt.

In other cases this denser contact facies may contain larger distinct crystals or phenocrysts and thus be a porphyry while the main mass is of even-granular texture. The phenocrysts may be anterior in origin to the time when the magma came to rest; in the main rock body they may be of the same size as the rest of the later rock grains but at the contact their contrast with the later dense material produces a porphyry. On the other hand, it has been observed that in many intruded masses of porphyry occurring in dikes and sheets the phenocrysts may be entirely absent at the contact margin, and in such rock bodies they have been formed after the period of intrusion, since if they had been brought up in the ascending magma they would be found at the contact as well as in the interior of the mass.

The cases treated above are sufficient to illustrate the chief endomorphic effects of contact metamorphism in igneous rocks.

Exomorphic Effects of Contact Metamorphism in General. The effect of the heat and vapors given off by an intruded mass of magma upon the surrounding rocks with which it is in contact varies with a number of factors. For one thing it naturally varies with the size of the intruded mass; it also varies with the nature of the vapors which are given off, as described under pegmatite formation. Another factor is the nature of the rock that is being affected, some kinds being more susceptible than others, and it also depends on the attitude of these rocks, that is, in the case of sedimentary beds, on the position of the planes of stratification toward the igneous mass. All of these are important features and each deserves separate treatment in order that the subject may be fully understood. In general it may be said that the most noticeable field evidence of the exterior effect is a baking, hardening or toughening of the surrounding rocks. It not uncommonly happens as a result of this process that they resist erosion better than the intruded mass or the unchanged enveloping rocks and thus give rise to distinct projecting topographic forms. This is admirably illustrated in the Crazy Mountains of Montana, where the resistant rocks of the contact zone give rise to a series of high ridges and peaks which encircle a more eroded mass of intruded igneous rock and rise sharply from a sloping plain of soft unchanged shales and sandstones. In the case of a dike it may thus occur that the dike and the surrounding beds are lowered more rapidly by erosion, while the contact walls on either side are left projecting as two parallel ridges.

The mineralogical effect is that, in general, where the agencies have made themselves most strongly felt there is a recrystallization of the rocks. This is produced by an interchange of the molecules within short distances whereby former chemical combinations are broken up and new ones formed. In mass, that is, in sum total, the chemical composition of the altered rock generally remains the same, except that volatile compounds, water, carbon dioxide, organic matter, etc., are driven out, and in some cases, volatile components, fluorine, boron, etc., may be added by the mineralizing vapors from the igneous mass.

Modes of Occurrence. The widest and most pronounced contact zones as a rule are noticed about the great intrusive stocks and batholiths. This is most natural, since the vast size of the igneous body supplies heat and vapors for a great length of time. Around them contact zones a mile and even more in breadth have been observed in many places. Next to them perhaps the most striking are seen about old volcanic necks. The breadth and intensity here often seem disproportionate to the size of the igneous mass but this is to be explained by the fact that the necks represent conduits through which fresh supplies of highly heated matter have been successively passing. This renewal of matter in the conduit may thus induce a superadded effect. In such cases there may be no endomorphic effect of cooling on texture as described above; the conduit walls are so highly heated that the texture of the igneous rock remains the same up to the very contact wall.

In the case of dikes considerable variations may be seen; in small dikes the effect may be noticed only a few inches or even less, while in large ones it may extend many yards on either side. Again, some dikes have served as conduits for magma passing up through them into larger intrusions above, feeding sheets or laccoliths or giving rise to extrusive outflows. About them the metamorphism will naturally be greater, other things being equal, than where a fissure was filled by a single charge of magma which immediately came to rest. For this reason the metamorphism induced by intrusive sheets and laccoliths is generally inconsiderable, since they also represent a single charge of magma into the rocks about them, which is not renewed. Immediately at the contact and for a few feet or yards beyond, the rocks may be altered but the effect soon dies out except in the cases of very powerful sheets and large laccoliths. With extrusive lava flows a small amount of baking or hardening of the rocks and soils on which they rest is often seen.

Position of the Rocks. It is a common thing to observe that the width of the contact zone varies considerably from place to place about the intrusive mass. This may be due to underground irregularities in the igneous rock body, a wide extension of the zone pointing to a corresponding extension of the mass below, as illustrated in Figs. 71 and 72. In the stratified rocks the position or attitude of the planes of stratification to the intrusive mass is also important. Thus in Fig. 73 the beds at *B* dipping into the mass of granite *C* tend to have their bedding planes and joints opened by the upward movement of the magma, and their position is such as to facilitate the entrance and wide extension of the vapors and heat, thus producing a broad contact zone. On the side *A* on the contrary the conditions are just the reverse of this and a much narrower contact zone is the result.

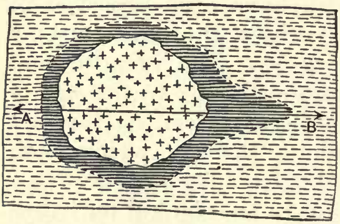


Fig. 71. Ground Plan or Map of an Intruded Stock and its Contact Zone.

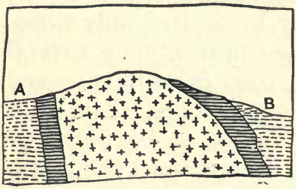


Fig. 72. Vertical Section along Line A—B in Fig. 71.

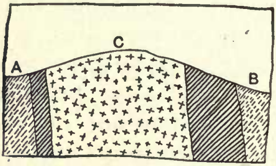


Fig. 73. Section showing width of Contact Zone depending on Position of Beds.

Effect on Different Kinds of Rocks. In a general way the most notable effects are produced on sedimentary rocks and these for purposes of consideration may be divided into the sandstones, limestones, clay shales or slates and their various admixtures. On pure quartz *sandstones* the effect is relatively slight though for short distances and in the near zone of most intensive action they are sometimes found hardened into quartzites. Pure *limestones* are recrystallized and changed into *marble* and not infrequently in large masses and extending over considerable distances. The most notable effects are produced when the limestones are impure, containing quartz sand and clay mixed with them. In this case the SiO_2 drives CO_2 out and carbonates are changed to silicates. If the limestone is a dolomite containing magnesia the results are more complex. Some of the simpler of these changes may be readily shown by equations which represent the chemical changes involved.

$$\overset{\text{Calcite}}{\mathrm{CaCO_3}} + \overset{\text{Quartz}}{\mathrm{SiO_2}} = \overset{\text{Wollastonite}}{\mathrm{CaSiO_3}} + \overset{\text{Carb. diox.}}{\mathrm{CO_2}}$$

$$\overset{\text{Dolomite}}{\mathrm{CaMg(CO_3)_2}} + \overset{\text{Quartz}}{2\cdot\mathrm{SiO_2}} = \overset{\text{Pyroxene}}{\mathrm{CaMg(SiO_3)_2}} + 2\,\mathrm{CO_2}$$

$$\overset{\text{Calcite}}{3\,\mathrm{CaCO_3}} + \overset{\text{Clay}}{\mathrm{H_4Al_2Si_2O_9}} + \overset{\text{Quartz}}{\mathrm{SiO_2}} = \overset{\text{Garnet}}{\mathrm{Ca_3Al_2Si_3O_{12}}} + \overset{\text{Carb. diox.}}{3\,\mathrm{CO_2}} + \overset{\text{Water}}{2\,\mathrm{H_2O}}$$

$$\overset{\text{Calcite}}{\mathrm{CaCO_3}} + \overset{\text{Clay}}{\mathrm{H_4Al_2Si_2O_9}} = \overset{\text{Anorthite}}{\mathrm{CaAl_2Si_2O_8}} + 2\,\mathrm{H_2O} + \mathrm{CO_2}$$

In some cases the rock is thus entirely changed into silicates or mixtures of them, but usually it consists of impure marble or altered limestone containing the minerals aggregated into lumps or bunches. Carbonaceous material which may be present is often changed into graphite. In addition to those minerals mentioned, a variety of others, whose origin depends on the mineralizing vapors given off by the igneous rock, may also be formed, such as mica (phlogopite), chondrodite, hornblende, vesuvianite, epidote, tourmaline, etc. In these cases the main materials are those already in the rock; the vapors furnish the volatile components, the hydroxyl, boron, fluorine, etc., needed for their composition. Such minerals furnish transitions to the more typical cases of pneumatolytic contacts mentioned below. It should not be forgotten also that many of these minerals contain oxide of iron, ferrous or ferric or both, and this must come from the limonite or other hydrated iron oxides mixed in with the impure marly beds and deposited with the other material at the time of their formation. Perhaps of the minerals mentioned garnets, pyroxenes and vesuvianite may be taken as among the most typical of such occurrences in altered limestones. Many instances of such contacts are known in various parts of the world and some of them have become famous for the variety and beautiful crystallizations of the minerals which they afford and which are to be found in all mineral cabinets.

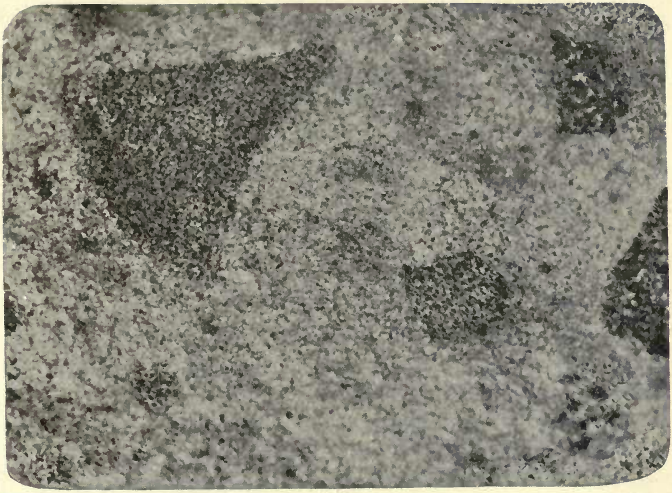
In the case of *clay shales* and *slates* variable effects are produced, but usually ones that are well marked and characteristic. While such rocks consist mostly of microscopic fragments of quartz, granules of clay, mica, etc., there is considerable variability in their composition and accordingly a difference in the result of the metamorphism. Sometimes they are baked into a dense, hard rock with conchoidal fracture, of a black or very dark stone color, called *hornstone*, which closely resembles trap or basalt. Sometimes they are like the hornstone in hardness, texture and fracture but differ in color, being of a light gray to green-gray or greenish and are known as *adinole*.

In other cases where the beds are more rich in kaolin, a mineral, andalusite, is apt to develop according to this formula:

$$\overset{\text{Kaolin}}{H_4Al_2Si_2O_9} = \overset{\text{Andalusite}}{Al_2SiO_5} + \overset{\text{Quartz}}{SiO_2} + \overset{\text{Water}}{2\,H_2O}$$

At the contact a rock composed largely of this, often in recognizable grains and crystals, and mixed with a brown biotite in glimmering specks, forms a granular rock, generally dark in color and much resembling an igneous rock in texture. All visible evidence of bedding of sedimentary character is lost. This would be termed an *andalusite hornfels*. Further from the contact the rock begins to lose its granular texture; it becomes more schist-

PLATE 12.



A. INCLUSIONS IN GRANITE.

B. FRUCHTSCHIEFER.

like or perhaps slaty and is dotted with the andalusite prisms. These very frequently gather up the dark organic matter of the rock and arrange it within themselves in the manner characteristic of this mineral. They then appear dark on a lighter background, as seen in Fig. 2, Plate 12, and this variety of rock is known as "Fruchtschiefer" (fruitschist) by the Germans. The rock has much the character of a fine-textured mica-schist.

Still further from the contact the effects of metamorphism are less and less marked, the beds show more and more of their original sedimentary nature; in this part the most evident effect is a spotting of the shales or slates from collection of organic matter or minerals into more or less well defined points or knots. Such a development of knots is one of the most characteristic features of moderate contact metamorphism and, when encountered in the field, should always lead to search for more intensive effects and the possible nearness of intrusive igneous rock bodies. The latter may of course be below and not yet exposed by erosion.

Just as all kinds of variations between sandstones, limestones and shales are found in nature, so do the different varieties of rocks produced by contact metamorphism, as described above, vary and grade into one another.

In the nature of things the already existent *igneous rocks* are less altered by the contact metamorphism of following intrusions than the sedimentary ones. This is particularly true of the granites and other very feldspathic rocks. The ferromagnesian ones, those containing feldspars rich in lime, and especially those composed chiefly of pyroxene, show at times considerable effects. The pyroxene is converted into hornblende and the rock becomes an amphibolite and even at times a hornblende schist.

Pneumatolytic Contacts. It was mentioned above in connection with the changes observed in limestones that minerals appeared whose origin was due to the mineralizing vapors given off from the igneous mass. At times in contact zones the outer rocks may be converted into masses of such minerals, testifying to the abundance and energetic action of the excluded vapors. Such minerals as tourmaline, topaz, fluorspar, vesuvianite, mica (muscovite), etc., ones containing hydroxyl, fluorine and boron are characteristic of these occurrences. The masses thus formed are not widespread and regular around the contact but appear here and there, especially near fissures, sometimes in isolated areas in the other rocks, sometimes in large, sometimes in smaller lumps and masses, following the irregular escape of the gases.

Contact Zones and Ore Bodies. In the contact zones of igneous rocks, the passage of the vapors and the movement of heated solutions in them, combined often with their own chemical composition, which causes them to react with the solutions, have made them especially favorable places for the deposit of ores. Their loss of volatile substances causes a reduction of volume, they become more porous, if not too deeply buried, and permit more easily the circulation of fluids. As a result of this we find many valuable deposits of the ores of gold, silver, lead, copper, etc., from magmatic waters, in such contact zones. In places in the mining regions of the Rocky Mountains the contact between sedimentary beds and intrusive masses of granite, porphyry, etc., from some elevated point may be followed with the eye for miles by the successive mines, pits, and heaps thrown out from prospects. So well is this known that contacts between porphyry and limestone are eagerly sought by every prospector. Any adequate treatment of this subject would carry us far beyond the limits of this work and further information should be sought in those treatises which deal with the origin of ore deposits.

Classification of Igneous Rocks.

Introductory. There is probably no subject in the domain of natural science concerning which there has been and is to-day less agreement than in the classification of igneous rocks. The reason for this is that there are no distinct boundary lines drawn by nature itself. The igneous rock masses of the earth possess certain features which may be used to distinguish and discriminate them, one from another, such as their geologic mode of occurrence, their mineral composition, their texture, and their chemical composition, which nearly represents that of the original magma. A very brief inspection serves to show, however, that in each of these features gradations exist without hard and fast lines. If we classify them according to mode of occurrence and divide them into intrusive and extrusive rocks, then, for example, it is clear that every lava flow is (or was) prolonged into depths below by an intrusive continuation in the form of a dike or volcanic neck. We should have to separate the intrusive from the extrusive at some point by an arbitrary plane; above this the rock would receive one name, below it another, though it is clear that the material just above and that just below would be absolutely alike. The same is true when we consider the other features of rocks mentioned; they are found to grade into each other mineralogically, chemically and texturally, and where lines are drawn it must be done arbitrarily. It is due to these facts that so much diversity of opinion has existed regarding their classification, some laying stress on one feature, some on another. By general common consent among petrographers, especially since the use of the microscope has served to reveal the composition of dense rocks, a large number of different kinds or types of igneous rocks are recognized, based primarily on the kinds and relative quantities of their component minerals and on their texture, but as to the manner in which these recognized kinds shall be grouped in a classification there is, as stated above, wide diversity of opinion. It would not be proper to go into the discussion of this subject further, but it should be clearly understood at the outset, that whatever method of classification of igneous rocks is used, the boundary lines must be artificial ones and in many cases just where a rock should belong must be a matter of opinion, which each must decide for himself.

Older Megascopic Classification. Before the microscope came into use in studying rocks, they naturally divided themselves into two groups, those whose component mineral grains were large enough to be seen and recognized and those which were too compact to permit this. The former group was divided into different kinds according to the mineral varieties composing them, the latter according to the color, texture, luster and other physical properties they presented. In this manner by common usage a megascopic classification, extremely useful for geologic and common purposes, came about, which gave rise to such terms as granite, diorite, porphyry, greenstone, basalt, etc.

Effect of the Microscope. When the microscope came into use it was discovered that the dense rocks could be studied and their component mineral grains determined, nearly as easily as the coarse-grained ones, and the result of these studies showed that a vastly greater diversity existed among them than had been suspected. And among the coarser-grained ones it was also found that many minerals, until then not known in them, existed, and that great variations among the minerals known to compose them could be seen, as well as differences in texture, etc. To express these differences among the rocks and to connote the ideas regarding them which they engendered, not only have a whole host of new rock names arisen, but the old megascopic terms have been defined and redefined by various authorities, until they have nearly all lost their original significance.

This has been an unfortunate phase of the history of the development of petrography as a science, because these former megascopic or field names, as we should term them now, served a very useful and necessary purpose, which the more exact and scientific nomenclature of modern petrography cannot replace. The person who desires to deal with rocks and name them from the megascopic, field point of view, such as the field geologist, the engineer, the architect, etc., is left without any equipment for doing so. A single illustration will suffice. The old term granite meant any granular igneous rock and then later one composed of quartz and feldspar. Now, as used by modern petrographers, it is only a granite in case the feldspar is chiefly alkalic, while if it is dominantly soda-lime feldspar, the rock is termed a quartz diorite, a distinction which ordinarily cannot be made without microscopic study.

The redefinition and specializing of these useful general field terms is very much the same as if the botanists had redefined such terms as bush, tree, vine, shrub, etc., and had made them the names of particular species or genera, so that if tree, for instance, were properly used, it would designate only oaks, or even *quercus alba*.

In the meantime in the world at large, where rocks are commercially dealt with, as in mining, architecture, etc., the use of rock names in the old way has gone on quite regardless of the petrographers, but the geologist or engineer who has endeavored to keep up with the development of the science and use its terms megascopically has carried an ever increasing load until finally he has been compelled to become a petrographer or else give up in large part any independent use of rock names. Without doubt it is largely due to this fact that every advance in the definiteness and completeness of petrographic scientific nomenclature has raised a wave of protest among geologists.

Present Need in Classification. It is clear that the parting of the ways has long been reached and it ought to be definitely recognized that the further development of petrology and of the classification and nomenclature of rocks from the scientific standpoint must be left largely to petrographers, while those who have occasion to deal with them in the purely megascopic manner must have a method of classification and a set of terms of a totally different scope and usage. They must in large measure revert to that which was in vogue before the microscope came into use.

It matters little whether such a classification is completely based on all the principles underlying scientific petrology which the study of rocks has revealed or not; to be useful it must be practical and to be practical it must be based entirely on the evident megascopic characters of rocks, such as can be seen by the eye or pocket lens or be determined by simple means at every one's command.

Classification used in this Work. As it is the object of this work to treat rocks from this point of view the following method of classification has been adopted.* First, the rocks are considered according to their texture and from this it will be found that they divide naturally into three classes, *grained* †, *dense*, and *glassy*.

A. Grained Rocks. By this is meant those rocks whose component mineral grains are large and distinct

---

* This is essentially that proposed by the author and several other petrographers. "Quantitative Classification of Igneous Rocks," by Cross, Iddings, Pirsson and Washington, University Chicago Press, 1903, p. 180.

† The term "grained" is here used instead of "granular" for two reasons. First, because granular (from granule — a little grain), strictly speaking, means fine-grained, while the rocks included may be coarse, medium or fine-grained. Second, because granular is used by many petrographers in a technical way as an equivalent to "even-granular" and opposed to porphyritic, while grained rocks may be either. *Phanerocrystalline, macrogranular, megagranular,* etc., have much the same meaning but it is better to use a simple English word than a compound Latin or Greek one.

enough to be seen and recognized by the eye alone or with the lens. No hard or fast line can be here drawn as to the size of grain; it will vary with the kind of mineral, their association together, and on the experience and skill of the observer. In general it may be said that it includes rocks whose average size of grain is as large or larger than that of ordinary loaf sugar.

B. Dense Rocks. This will include those which are nearly or wholly of stony appearance and texture but whose minerals cannot be determined, because the constituent particles are too minute. They may even appear homogeneous but are generally microcrystalline.

C. Glassy Rocks. Includes those wholly or in part made up of glass, as shown by their vitreous or pitchy luster, conchoidal fracture, and other characters and appearance.

Treatment of Porphyries. Reference is had in the above to rocks whose average size of grain is uniform or nearly so. But, as explained in the description of the porphyritic texture on page 156, many igneous rocks are porphyries, that is, they contain distinct crystals or phenocrysts much larger in size than that of the average grain of the groundmass in which they lie embedded. It is assumed that in general the size of the phenocrysts is such that they can be distinctly seen and the particular kind of mineral composing them can be recognized or approximately determined. In classifying porphyries they at once naturally fall into two classes; first, (D) one in which not only the phenocrysts, but also the mineral grains of the groundmass are large enough to be determined and second, another (E) in which the groundmass is either too dense to be made out or (F) glassy. In the former case (E), two subdivisions can be made, one (*a*) in which the phenocrysts are very abundant and a good idea of the mineral composition of the rock as a whole may be had and another (*b*) in which the amount of groundmass is predominant and this cannot be done.

For a clearer understanding these divisions of porphyries may be shown in tabulated form.

D. Groundmass grained, recognizable.
E. Groundmass dense, unrecognizable.
  a. Phenocrysts very abundant and recognisable.
  b. Phenocrysts not very abundant or rare, groundmass very abundant.
F. Groundmass glassy.

It would be logical to make the same subdivisions *a* and *b* under class F as are made in E but cases where glassy groundmasses are filled with abundant recognizable phenocrysts dominating in amount over the groundmass though known, are not sufficiently common to make worth while the subdivision for practical purposes.

No sharp lines can be drawn between these divisions; they pass into one another gradually, except as to whether the rock is glassy or stony in texture.

It is to be observed that since the rocks belonging in division D have their mineral constituents determinable they belong in the same category as those in A of the evenly granular ones previously mentioned, so far as this particular is concerned. Likewise in division E, subdivision *a*, if half or more of the rock is composed of recognizable phenocrysts its general mineral character can be determined and it falls in the same category. But in the remaining divisions not enough of the mineral characters can usually be told to safely identify the rocks on this basis and such rocks are evidently to be classed with division B, dense rocks and C, glasses which are not porphyries and which cannot be subdivided according to mineral composition.

Subdivisions of Class A. The igneous rocks having been divided into classes on the basis of texture it now remains to show on what grounds these classes can be further subdivided and the individual kinds of rocks, from the megascopic standpoint, obtained. This is done, as already suggested, in the *even-* and *porphyritic-grained* rocks by considering their mineral composition. First we may broadly divide them into two main groups.

a. Rocks in which the feldspars or feldspars and quartz predominate.
b. Rocks in which the ferromagnesian minerals (pyroxene, hornblende, olivine, etc.) predominate.

As a rule, the rocks of the first group are light-colored, white, red or gray, but this is not an absolute rule since the feldspars are sometimes very dark from an included pigment. In general the rocks of the second group are dark in color to black but this is also not an invariable rule since some, like those composed wholly of olivine, are rather light.

The first group *a* may be further subdivided on the basis of the relation of quartz to the feldspars. Those which contain an appreciable amount of quartz with the feldspars fall in one division and are termed *granite,* when even granular in texture, and *granite porphyry,* when of porphyritic texture, while those in which quartz is absent or is present in inappreciable quantity are called *syenite* and *syenite porphyry* respectively. Further division of these into varieties on the basis of particular mineral characters will be considered in the description of them in the succeeding chapter.

The second group *b* is subdivided on the basis of the relation of the feldspars to the ferromagnesian minerals, into those which contain feldspar, subordinate in amount to the ferromagnesian minerals, and those in which it is wanting. Thus we have as follows:

c. Rocks with predominant ferromagnesian minerals. feldspar subordinate.
d. Rocks consisting wholly of ferromagnesian minerals.

Group *c* is subdivided according to the nature of the predominant ferromagnesian mineral present. For practical purposes there need be only two considered here; if it is hornblende the rock is *diorite,* if it is pyroxene it is *gabbro.* The means for distinguishing between hornblende and pyroxene are discussed in the description of these minerals in a preceding part of this work. In many cases, especially in the finer-grained rocks of this group, it may not be possible to distinguish between hornblende and pyroxene and the rock may then be termed *dolerite.* This name would then mean that the rock consisted chiefly of indeterminable predominant ferromagnesian minerals with subordinate feldspar.*

Porphyries occur in this group but they are relatively of less importance than in the preceding ones; they are treated in the descriptive part. Rocks in which ferromagnesian minerals, other than hornblende and pyroxene, predominate over feldspar are known but are of little practical importance in a megascopic scheme of this character and are therefore omitted. They will be mentioned later.

The last group *d,* consisting wholly of ferromagnesian minerals, is divided according to the kinds of these minerals present. The most common and prominent mineral in the group is pyroxene but this is usually associated with olivine and the rock is termed *peridotite.* This is the most common member and may be used as a general term for the group. If olivine is absent and the rock consists wholly of pyroxene it is *pyroxenite,* if of hornblende, *hornblendite.* Varieties are described under peridotite.

---

* In this usage of dolerite the author adopts and follows that proposed by Chamberlain and Salisbury (Geology, vol. 1, p. 431, 1904) which is already obtaining considerable vogue and from such authority is likely to become general. In Germany the term is restricted to certain coarse-grained basaltic rocks; in England it has had a certain use for all coarse-grained basalts and for rocks termed elsewhere diabases; in America it has been little employed and may well be revived as a field name in the sense suggested. With this meaning it is a very useful term. The word is from the Greek, meaning deceptive, with the idea that the pyroxene cannot be distinguished from the hornblende.

Porphyries in this group rarely occur and are of no practical importance.

In summation, in considering the classification of the group of grained rocks whose constituents are determinable, one should consult what has been said regarding the chemical composition of igneous magmas and the variations in mineral composition beginning on page 141. It is not possible, however, to classify them entirely, for megascopic purposes, by the diagram given on page 145, for, in general, we cannot discriminate between the different kinds of feldspars. Thus the rock there shown as quartz diorite must be classified under the head of granite, while, as compared with the diagram, the diorite and gabbro mentioned above broadly overlap. Still, in a general way, bearing these exceptions in mind, the classification, distinguishing between the feldspathic and the ferromagnesian rocks, brings out the ideas there expressed. The rocks of this class are nearly always intrusive, rarely extrusive.

Subdivisions of Class B. In considering the second class of rocks, B, whose texture is so fine or dense that the mineral grains cannot be determined, we have little with which to classify them for field purposes except the color. They are thus divided into two groups, the light-colored and the dark-colored. Of course if the rock is either white or black there can be no difficulty in assigning it to one or the other of these two divisions, but all gradations of color exist and it is often a matter of pure choice to which a particular rock should belong. Evidently some closer definition of the terms is needed. We may do this as follows. The term *dark* includes rocks that are *very dark gray, very dark green* or *black;* all other colors, *white, red, purple, yellow, brown,* light and medium *gray,* light and medium *green* are *light.* The latter are known under the name of *felsite,* while the former or dark rocks are *basalt.* The division thus made also expresses in a general way an important fact concerning their composition, for the former are derived from magmas, which, under different physical conditions producing coarser-grained rocks, would crystallize as granites and syenites. On the other hand, the basalts represent the diorites, gabbros and peridotites in dense or fine-textured forms. While many exceptions will be found, this general rule holds true and the light rocks as defined above are chiefly feldspathic, the dark are mainly ferromagnesian.

While the rocks of this group are often of homogeneous texture and aspect, they are also very often porphyritic. If the amount or bulk of phenocrysts in relation to the fine or dense (aphanitic) groundmass is very large, say half the mass of the rock or more, such porphyries pass back into class A, of grained rocks as previously explained. But if the amount of phenocrysts is less to much less than the groundmass then we have *felsite porphyry* and *basalt porphyry* respectively, according to the color of the groundmass. It has also been suggested that they may be called *leucophyre* (light-colored porphyry) and *melaphyre* (dark-colored porphyry), respectively.* Further subdivisions of these porphyries can be made according to mineral character of the prominent phenocrysts. Thus we might have *quartz-felsite-porphyry; feldspar-felsite-porphyry; hornblende-felsite-porphyry* or *quartz-*, *feldspar-* and *hornblende-leucophyre*, and similarly we have *augite-basalt-porphyry*, *mica-basalt-porphyry*, *feldspar-basalt-porphyry* or *augite-*, *mica-* and *feldspar-melaphyre*. Many combinations of this kind can be made but the above will suffice as examples. The rocks of this class are sometimes intrusive, sometimes extrusive.

Subdivisions of Class C. The rocks of the third class, C, those wholly or partly of glass, are distinguished by their glassy or resinous luster and want of stony texture. They may be classified as follows:

OBSIDIAN, luster strong, bright, glassy; color usually black, sometimes red, more rarely brown or greenish.

---

* Quantitative Classification of Igneous Rocks, p. 184.

- Pitchstone, luster resinous or pitch-like; colors various, as above, but black less common.
- Perlite, glassy rock with perlitic structure, produced by small spheroidal fractures; usually gray in color.
- Pumice, highly vesicular glass (see page 158), usually white or very light-colored.

Any of these may be porphyritic or not; though cases of porphyritic pumice are much less common than in the other three. When porphyritic a general name for them is *vitrophyre* (glass porphyry) and different varieties may be distinguished, as in the porphyries of the class above, according to the kind of predominant phenocrysts; thus *quartz-vitrophyre*, *feldspar-vitrophyre*, etc. The rocks of this class are practically wholly confined to extrusive lavas.

Class D. In addition to the three main classes of igneous rocks described above we may add as an appendix in a fourth class, D, the fragmental material thrown out in volcanic eruptions and already mentioned on page 140 as *tuffs* and *breccias*.

Such material serves as a connecting link between the sedimentary and igneous rocks. For, as it falls through the air, it becomes assorted as to size, and successive outbursts thus produce rough but distinct bedding. Or it may fall into water and become perfectly stratified. Falling on the land it may cover vegetation and contain fossil imprints of plants, leaves, etc.; or if into water, of marine organisms. Thus if we classify volcanic ash beds as igneous rocks we cannot say that a distinguishing feature of igneous rocks is that they never contain fossils. See remarks on page 133.

Classification Tabulated. The classification which has been adopted and described in the foregoing may now be shown, for convenience of reference, in tabulated form on the following page.

Classifications based on Microscopic Research. In the classification previously described, the color and texture of rocks play a prominent part, and mineral composition can be used only in an approximate manner. But where

MEGASCOPIC CLASSIFICATION OF IGNEOUS ROCKS.

A. Grained (Phanerites). Constituent Grains Recognizable. Mostly Intrusive.				
	a. Feldspathic rocks, usually light in color.		b. Ferromagnesian rocks, generally dark to black.	
	With Quartz.	Without Quartz.	With subordinate Feldspar.	Without Feldspar.
Nonporphyritic.	GRANITE. a. Aplite.	SYENITE. a. Syenite. b. Nephelite Syenite. c. Anorthosite.	DIORITE. GABBRO. DOLERITE.	PERIDOTITE. Pyroxenite. Hornblendite.
Porphyritic.	GRANITE-PORPHYRY.	SYENITE-PORPHYRY.	DIORITE-PORPHYRY.	
B. Dense (Aphanites). Constituents Nearly or Wholly Unrecognizable. Intrusive and Extrusive.				
	a. Light colored, usually feldspathic.		b. Dark colored to black, usually ferromagnesian.	
Nonporphyritic.	FELSITE.		BASALT.	
Porphyritic.	FELSITE-PORPHYRY.		BASALT-PORPHYRY.	
C. Rocks Composed Wholly or in Part of Glass. Extrusive.				
Nonporphyritic.	OBSIDIAN, Pitchstone, Pearlite, Pumice, etc.			
Porphyritic.	Vitrophyre (Obsidian-, and Pitchstone-porphyry).			
D. Fragmental Igneous Material. Extrusive.				
TUFFS, BRECCIAS (Volcanic ashes, etc.).				

rocks are studied in thin section under the microscope texture becomes of much less importance; all of the minerals and their exact characters can be discovered and their relative proportions made out. In this more exact work the kinds of rocks that are recognized by petrographers are based primarily on the kinds and to some extent the relative proportions of the component minerals. This makes a great number of kinds of rocks which have been named. Generally they are grouped first, according to minerals and second, according to texture; some petrographers lay weight also on their mode of occurrence, whether extrusive or intrusive, while others add to this the genetic relations or groupings which they show in nature. Classifications have also been proposed in which their chemical composition plays the most prominent part.

Quantitative Classification. Recently several petrographers, including the author, have proposed an exact scientific classification of igneous rocks based on their chemical composition, expressed, however, in terms of minerals of definite composition, called standard minerals. For this purpose a chemical analysis of the rock is necessary but, where this cannot be obtained, an approximately correct result may be achieved by measurement of the minerals under the microscope, computing from this their relative bulk and weight, and, their composition being known, reckoning from this the chemical composition of the rock as a whole, as if obtained by chemical analysis.

The chemical composition is then computed, according to a set plan, into the relative amounts of standard minerals. These standard minerals are divided into two main groups; one characterized by the presence of alumina and silica, such as the feldspars, nephelite, corundum and quartz, but without iron or magnesia, the second characterized by iron and magnesia but without alumina, such as olivine, diopside, hypersthene, aegirite and iron ores. The complex ferromagnesian minerals which contain alumina, such as hornblendes, biotite, augite, etc., are not treated as standard minerals because it is better to consider them as compounds of simpler molecules of the two preceding groups. The first of these is called the *salic* (Si and Al) the second the *femic* (Fe and Mg) groups of standard minerals and the composition of the rock computed in quantities of them is called its *norm,* which may thus, when hornblende or biotite are really present in it, differ considerably from its actual mineral composition or *mode.*

All igneous rocks may be expressed in salic and femic minerals and according to the relative amount of each group as compared with the other they are divided into five classes, *persalane,* nearly or entirely composed of salic minerals (sal: fem $> 7:1$); *dosalane,* mostly salic

$$\text{(sal: fem} < 7:1 > 5:3\text{)};$$

salfemane, equal or nearly equal quantities of each

$$\text{(sal: fem} < 5:3 > 3:5\text{)};$$

dofemane, mostly femic minerals (sal: fem $< 3:5 > 1:7$); and lastly *perfemane,* nearly or entirely femic

$$\text{(sal: fem} < 1:7\text{)}.$$

Up to this point it is possible to use this classification in a megascopic manner. The *classes* thus obtained are subdivided into *orders* on the relations of the salic minerals, quartz, feldspars and feldspathoids (generally nephelite), to one another in the first three classes and on somewhat similar relations among the femic minerals in the last two. More minute consideration of the mineral oxides divides the orders into *rangs* and the rangs into *grads.* The proportions by which they are thus divided are always the same as that by which classes are made.

Further details regarding this and other systems of classification founded upon results obtained by microscopical research are to be found in the list of works mentioned on page 10.

CHAPTER VII.

DESCRIPTION OF IGNEOUS ROCKS.

Grained Igneous Rocks.

As explained under the section on classification the grained igneous rocks are those whose mineral grains are approximately of equal size and large enough to be identified with eye or lens, aided when necessary by chemical or physical tests. Those rocks whose grain is too fine to permit this will be found under the heading of the dense igneous rocks. The porphyries, the major part of whose constituent minerals can be distinguished, are described in the following section.

GRANITE.

Composition. Granites are granular rocks composed of feldspars and quartz. Sometimes they consist of these minerals alone but generally there is more or less mica present and often hornblende.

The *feldspar* is the predominant mineral and is readily recognized by its appearance and cleavage. Sometimes only one kind of feldspar is present but generally there are two, orthoclase and soda-lime feldspar. They may sometimes be distinguished by their colors; if one feldspar is flesh-colored to red while the other is white, gray or yellow, it is pretty certain that the first is orthoclase, the second soda-lime feldspar (plagioclase). Close inspection of a cleavage surface of the latter with a lens may show the twinning striations (see page 38) but the grains are rarely coarse enough to permit this. Rocks in which the amount of plagioclase is greater than the orthoclase are called *quartz diorites* by petrographers and are placed in a separate family, but this cannot be done in megascopic determination and they are all here classed as granites. They have also been called *granodiorites* in the western United States.

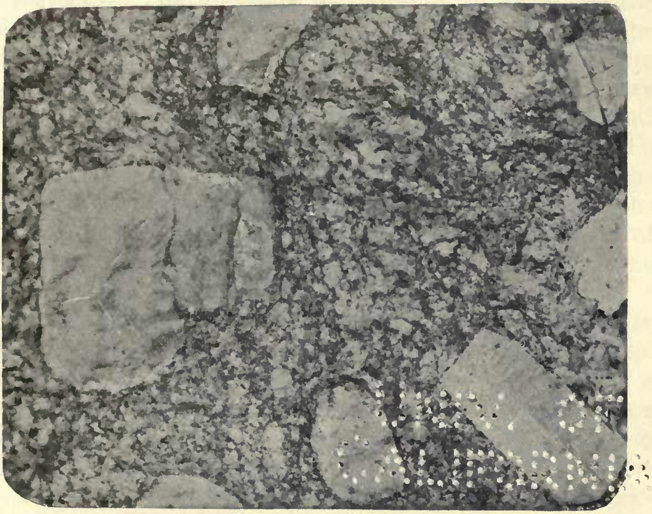
Quartz normally occurs as formless material, filling the interstices between the other minerals and hence without definite shape. The normal color is white to dark, smoky gray; sometimes it is red from included hematite, more rarely a bluish color. In the finer-grained granites the color is usually light or white, especially in those of a sugar granular texture. It is recognized by its oily, greasy luster and conchoidal fracture. In porphyritic granites it sometimes occurs in large dihexahedral crystals or round grains.

The *mica* may be either the light or colorless muscovite or black biotite or both kinds may be present. Cases where muscovite is the only mica are rare. Hornblende occurs in black to dark green grains or prisms. It is sometimes the only dark mineral but is more usually accompanied by biotite. These are the chief minerals, but if the rock is fairly coarse-grained, close inspection will commonly show occasional metallic-looking specks or grains of iron ore. Sometimes other minerals may be seen, brassy crystals of pyrite, dark red grains of garnet, etc., but these are occasional and are not of importance in determining the rock.

Texture. In ordinary normal granite the texture is an even granular one and alike in all directions through the rock. From this type insensible gradations, sometimes in the same mass, may be observed into the texture of gneiss which becomes noticeable through the linear arrangement of the components, especially the micas. Thus the rock passes into granite gneiss. The normal texture is shown on Plate 13. In other cases a tendency may be noted for some of the orthoclase crystals to be larger than the average grain and of more distinct crystal form. In this way the rock becomes porphyritic and

PLATE 13.

A. COMMON GRANITE.



B. PORPHYRITIC GRANITE.

when this is pronounced it is the porphyritic granite described below. Often the dark minerals tend to group or bunch together in spots.

Color. The general color of the rock depends largely on that of the feldspar and in the proportion of this to the dark minerals. Thus the color shades from white into gray to dark gray, resulting from the mottling by the biotite, etc. Such types are very common wherever granites are abundant, as in New England. More rarely the quartz and feldspar are themselves gray to dark gray and thus determine the color. An example of this is the granite of Quincy, Mass., largely used as a building stone. Another very common type of coloring is one in which the rock is flesh-colored, pink to red and even deep red. Such red granites are found in Maine, Missouri, Colorado, Scotland and other localities and are largely quarried and used for building.

Varieties. The varieties of granite depend on the relative proportions of the light and dark minerals, the color and the texture. The relative amount of the biotite (or hornblende) to the quartz and feldspar may vary widely; it may be entirely wanting or it may be present in large amount and make the rock quite dark. Such extreme cases are less common. The grain may become as coarse as large peas or even larger. These variations combined with those in color produce distinct types of granite which have often received local names. Some other varieties are described in following sections.

Porphyritic Granite. As mentioned above the feldspar may partly occur in large distinct crystals or phenocrysts. Strictly speaking this would cause the rock to become a granite porphyry but where the groundmass in which these lie is as coarse as an average granite it is the custom to speak of it as porphyritic granite, laying stress on the character of the groundmass rather than on the porphyritic quality. The feldspar phenocrysts are of orthoclase and have the forms shown under feldspar, page 35.

Reflection of light from the cleavages of these on the rock surface often shows they are in twin halves, due to Carlsbad twinning. The size of these phenocrysts is sometimes quite large, an inch long and broad or even more. An illustration of this type of granite is seen on Plate 13. Such rocks occur in New Hampshire and other localities in New England, in Colorado, in the Sierra Nevada Mountains, in England (Dartmoor and elsewhere), in the Black Forest region and other places.

Chemical Composition. The mass compositions of a few selected granites are shown in the analyses given here to illustrate the kind of magma from which such rocks have crystallized.

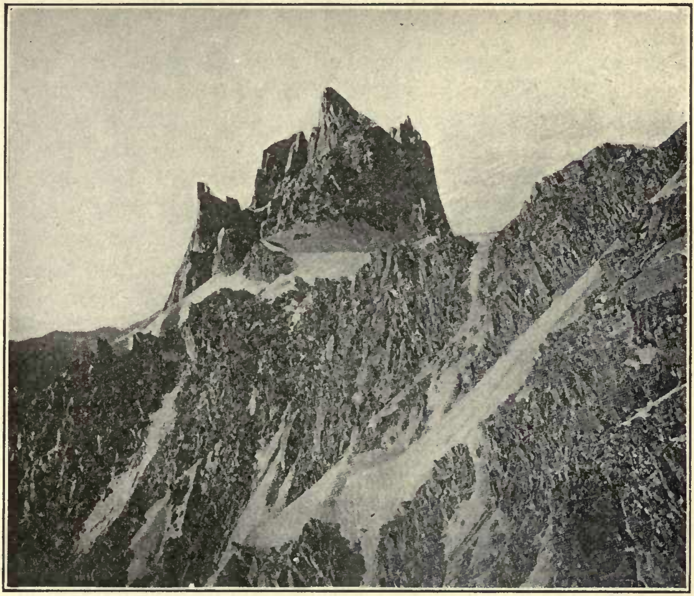
ANALYSES OF GRANITES.

	I	II	III	IV	V
SiO_2 .	77.6	74.4	71.2	68.0	66.3
Al_2O_3 .	12.0	13.1	13.7	17.2	16.0
Fe_2O_3 .	0.6	0.7	1.7	3.1	1.8
FeO .	0.9	0.9	1.0	0.4	1.9
MgO .	trace	0.4	0.8	1.2	1.1
CaO .	0.3	1.3	2.3	2.9	3.7
Na_2O .	3.8	2.6	3.6	3.2	4.1
K_2O .	5.0	6.1	3.8	3.9	3.5
H_2O .	0.2	0.3	1.7	...	0.5
XyO* .	0.2	0.4	0.2	...	0.9
Total .	100.6	100.2	100.0	99.9	99.8

* XyO = small quantities or traces of other oxides.

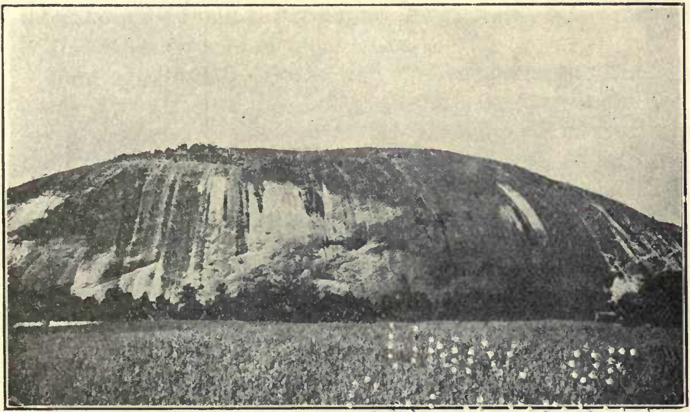
I, Hornblende Granite, Rockport, Mass.; II, Biotite Granite, Crazy Mountains, Montana; III, Granite, Conanicut Island, Rhode Island; IV, Granite, Kirkcudbright, Scotland; V, "Granodiorite or quartz diorite," Mariposa County, California.

The large percentages of silica, alumina and alkalies explain the predominance of feldspars and quartz. With the increasing lime in the last two, the alkalic feldspars give place in precedence to plagioclase; the increasing



A. EROSION OF GRANITE IN THE HIGH ALPS.

(After Duparc.)



B. EROSION OF GRANITE IN OLD AND LOW MOUNTAIN REGIONS, STONE MOUNTAIN, GEORGIA.

(Georgia State Geological Survey.)

iron and magnesia show increasing amounts of the dark minerals; coincidently with this the silica falls; the amount of free quartz is less and such rocks approach the next class, the syenites.

Physical Properties. The *specific gravity* of granites varies with the kinds and relative amounts of the component minerals; from 2.63–2.75 is the ordinary range, those containing more ferromagnesian minerals being the heavier. The average weight of a cubic foot of granite is about 165 pounds. Usually the porosity of such granites as are quarried for building purposes is very small, the percentage of water absorbed, compared with the weight of the dry rock, being about 0.15 of one per cent. Thus a cubic foot of average granite if completely saturated would absorb about 4 ounces of water. The strength of granites in resistance to crushing is very great and probably far greater than any load they would be called upon to bear in architectural work. A series of Wisconsin granites tested by Buckley showed crushing strengths varying from 15,000–40,000 pounds per square inch; some of these were very high, and from 15,000 to 20,000 is perhaps the average. As the pressure at the base of the Washington Monument is 342.4 pounds per square inch, it will be seen there is an ample reserve in most cases.

Uses of Granite. As is well known, on account of its great strength and durability, granite is extensively used for architectural purposes. Its pleasing colors and the high polish it takes cause it to be employed as an ornamental stone in interior work, in monuments, etc. In one respect, however, many granites have a defect which somewhat impairs their value for use in buildings in large cities. This defect is that they do not resist fire well, but crack, scale and sometimes crumble under great heat. One reason for this is that the quartz grains are very commonly filled with minute bubbles containing water or liquid carbonic acid gas (CO_2) or both.* They are so minute that they are often only to be detected with

---

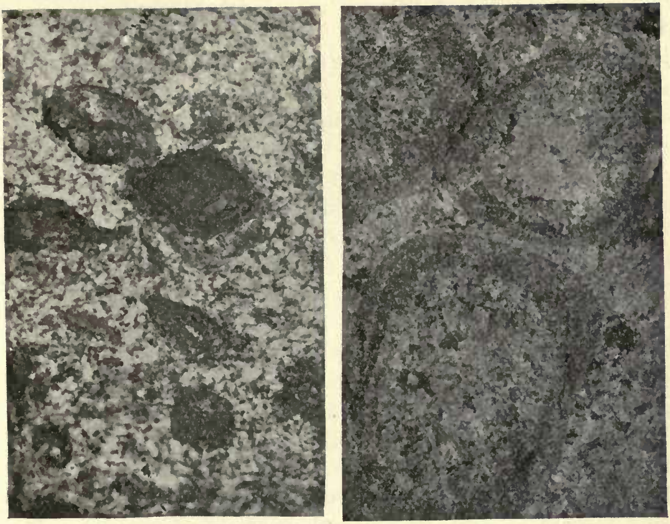
* The different rates of expansion of quartz and feldspar are another cause.

high powers of the microscope in thin sections but they may absolutely swarm in the quartz and constitute an appreciable fraction of its bulk. They represent material taken up or included at the time of its crystallization. Under the action of heat the pressure on these sealed crystal flasks becomes enormous; each quartz grain becomes, so to speak, a veritable tiny bomb and eventually it must crack in all directions and crumble and thus injure the strength and resisting capacity of the stone. Feldspars practically never suffer from liquid inclusions, like quartz, nor do the other ordinary rock minerals, so that rocks like syenite or diorite, in which quartz is absent or only sparingly present, make in respect to resisting fire much better stone than granite.

Jointing in Granite. Granite tends to a block jointing on a large scale in the great stocks. There generally tends to be three distinct sets of joints, two of which approximate to the perpendicular, the third to the horizontal. Sometimes these are nearly at right angles producing cubes, more often at angles which make rhomboidal blocks. Sometimes the horizontal one is most pronounced and the mass has a sheeted or layer-like character suggesting bedding. In dikes the joints are much more numerous and the mass breaks into small blocks, plates, etc. This jointing of granite is a matter of much importance in work of excavation, in mining, tunnelling, quarrying, etc., in facilitating removal of material, but it also explains why every granite mass is not suited to furnish material in blocks of sufficient size for constructional purposes. Quarries like those in Finland, in the so-called Rapakiwi granite, from which the base, a cube of 30 feet, and the shaft, 100 feet high by 15 feet in diameter, of the Alexander monument in St. Petersburg were taken and those in Egypt from which the great obelisks were cut are not common. Compare Plate 10.

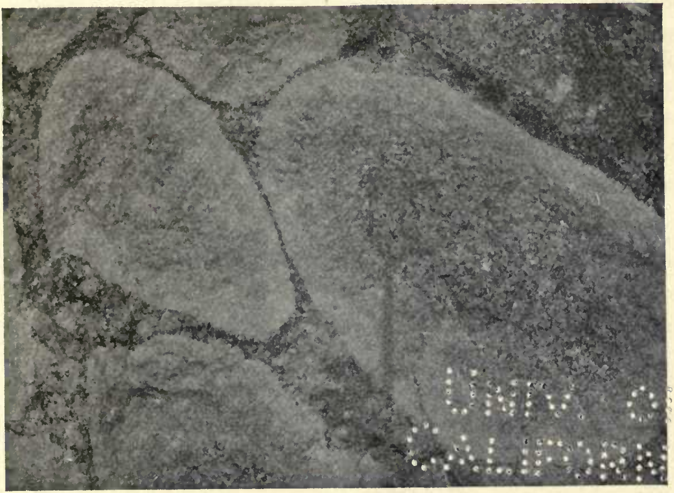
Erosion Forms of Granite. The jointing of granite largely conditions the work of erosive agencies on the

PLATE 15.



A. Craftsbury, Vermont.

B. Kortfors, Sweden.



UNIV. OF CALIFORNIA

C. Stockholm, Sweden.

ORBICULAR GRANITES.

mass but the topographic forms produced also depend greatly on the severity with which these act. In the high mountain chains and wherever they are very energetic, spires, needles and castle-like forms are produced, but in the lower massive and older ranges and where glaciation has been pronounced the granite stocks form more smoothly modeled, rounded or dome-shaped masses with gentle slopes and broad valleys, such as are seen in the hills and mountains of New England and in parts of Great Britain. The views on Plate 14 are illustrative of this.

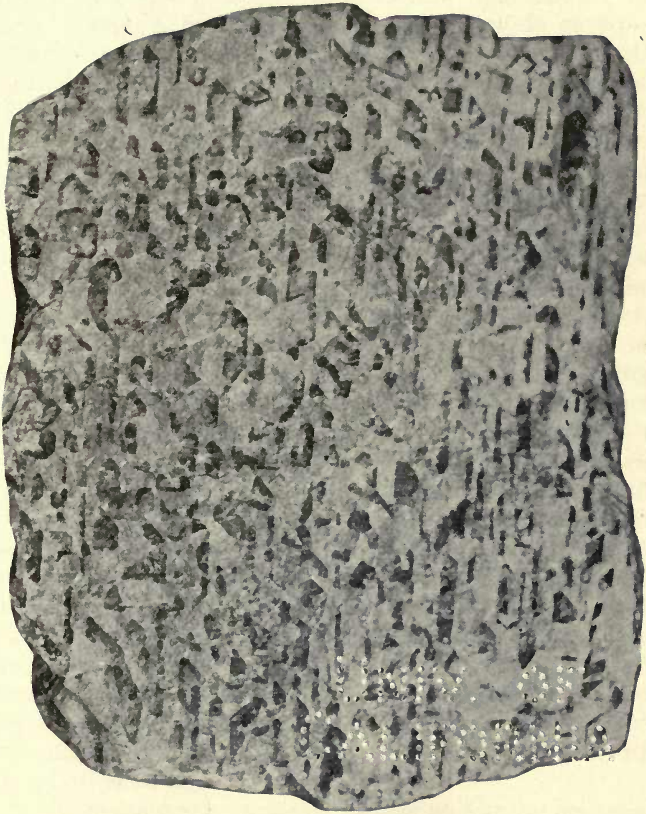
Orbicular Granite. It sometimes happens that the component minerals of a granite, instead of being uniformly distributed in grains of about the same size, are collected in some spots in an unusual way and arranged in ovoid or spherical bodies. Thus in a granite from Craftsbury, Vermont, called " pudding granite," the rock is full of nodules, varying from the size of a pea to that of a nut, composed almost entirely of agglomerated leaves of black mica, as seen on Plate 15. More commonly the bodies are composed of several minerals and consist of a nucleus with a concentric outer shell or shells. The component minerals are the same as those in the main body of the rock but their proportions differ in the nucleus and in the shells, sometimes consisting mostly or entirely of salic minerals, while some shells consist mostly of ferromagnesian ones. Their appearance is shown on Plate 15.

The bodies are round, ovoid and often lenticular or spindle shaped, as if drawn out. It was formerly thought that they represented pebbles and were a proof of the metamorphic origin of granite from conglomerates, but the arrangement and regular internal structure of the ovoids precludes such an idea and it is now generally held that they are due to some process of differentiation or aggregation of material in the magma with subsequent crystallization, though in some cases it is thought that they may represent inclusions of other rocks which have been melted up and recrystallized. Granites of this kind are called *orbicular* and though not common they have been described from Sweden, Finland, Corsica, Canada and Rhode Island. Similar structures have also been found in diorites and gabbros.

Miarolitic Structure. The older and deeper seated granites and especially those which have been subjected to heavy mountain making pressures show little or nothing of the miarolitic structure described on page 159. The conditions have been unfavorable for the formation of such cavities or under the pressure they have been obliterated. In other occurrences and in the younger, higher or unsqueezed granites these cavities may occur, and on their drusy surfaces fine crystallizations of the minerals may be seen. The crystals from such cavities in the granite of the Pike's Peak region in Colorado, from the Mourne Mountains in Ireland, from Baveno on the Lago Maggiore in Northern Italy and other localities are well known in mineral collections.

Pegmatite Dikes. These are very common in granites, so much so, that when this word is used a granite pegmatite is usually understood unless the rock is otherwise specified. They have the general characters described on page 175 and the following ones. The chief minerals are *quartz* and *feldspar*, the latter being mostly *orthoclase* or the variety of it called microcline, though albite also occurs. The quartz and feldspar are apt to be intergrown in such a manner that the interstices of a spongy quartz crystal are filled by an equally spongy feldspar crystal, the two sponges thus mutually filling each other's interstices and interclasping. As the quartz has no cleavage while the feldspar has, the cleavage through the intergrown mass is that of the feldspar and upon such surfaces the quartz appears, repeating its tendency to crystal form again and again and thus producing figures which recall the script used in Arabic writings. This arrangement is called *graphic granite* and a figure of it is seen on Plate 16. It

PLATE 16.



GRAPHIC-GRANITE, OR PEGMATITE.

shows that these two minerals have crystallized simultaneously. The minerals occur also separately and often in huge crystals so that such dikes are mined for commercial purposes, the quartz and feldspar being used in several technical processes such as the manufacture of china, porcelain ware, etc. The large crystals of *muscovite mica* which occur in them are the source of this material as used in stove windows, lamp chimneys, paper making, etc. In addition to these chief minerals a great variety of accessory ones are found, some of the more common of which are *tourmaline, garnet, beryl,* and *spodumene* among the silicates, *apatite, triphylite,* and a series of related phosphates, and a variety of kinds containing rare earths. Some of these minerals like the colored tourmalines, topaz, beryl, etc., are valuable for the material suitable for cutting into gems which they afford; others are useful as sources of the rarer elements used in chemical and some technical processes such as the making of Welsbach mantles. A full list of all the minerals known to occur in these pegmatites would cover a large proportion of all the kinds known in mineralogical science.

Inclusions. Schlieren. It is not uncommon to find in granite the various kinds of inclusions described on page 163 and the following. Sometimes the composition and form of these show that they are fragments of previously existing rock formations broken off and engulfed in the granite magma. These are most common near the border of the mass. They may vary in size from an inch across or less to masses a number of yards long. When they are found in the center of the mass they may be suspected of having sunk into it from the former overlying roof of other rocks.

In other cases the apparent inclusions are the *schlieren* described. They may consist wholly or nearly so of quartz and feldspar and thus be very light in color or extremely rich in biotite or hornblende or both, with iron ore, and thus be very dark in color. Such dark streaks may at times be due to melted up inclusions but in other cases they may be caused by aggregations of the normal dark minerals of the granite and in general are ascribed to processes of differentiation.

Complementary Dikes. Very frequently it will be found that bodies of granite are cut by complementary dikes as described on page 167. The *leucocratic* ones are commonly composed almost solely of quartz and feldspar with which is usually associated a little white mica. The rock has a granular appearance and this variety of granite is called *aplite*. Sometimes small black specks of biotite or hornblende or of black tourmaline may be seen in them but always the dark minerals play a very subordinate rôle. The color of these rocks is nearly constantly very light, white, flesh-color, pale yellow, gray or brown being common. Sometimes these rocks are so fine of grain that they pass into felsites of the colors mentioned, and sometimes they are porphyritic with phenocrysts of quartz or feldspar or both and are thus granite or felsite porphyries. But most commonly they are even-granular with a grain about like that of loaf sugar and the dike is the characteristic mode of occurrence. They are mostly noticed cutting the granite mass, less commonly the surrounding rocks. They are of all sizes, from a fraction of an inch to a number of yards in breadth. If the larger ones are traced along the outcrop it may sometimes be found that they change into pegmatite dikes.

The *melanocratic* dikes, sheets, etc., complementary to the quartzo-feldspathic aplites described above, are dark to black heavy rocks of basaltic aspect. They are composed chiefly of biotite-mica, hornblende, pyroxene and iron ore with feldspars, but very commonly the grain is too fine for these minerals to be distinguished and they are to be classed as basalts, or, in allusion to their mode of occurrence, they may be termed lamprophyric basalt. In many cases, however, when biotite is the prominent ingredient they have a characteristic glimmering appearance or the plates of biotite may be distinctly seen, and in this case they are known as *mica traps*. The most characteristic color of these rocks is a dark stone gray. Occasionally porphyritic crystals of hornblende or of feldspar, as well as of biotite, appear in them and not uncommonly fragments of the granite which they cut and of other rocks. They also at times contain sulphurets of the heavy metals, usually pyrite, and on this account have been prospected or mined as if ore veins, generally without much result. They alter and weather down into soft greenish material full of chlorite or into brown earthy masses. The earlier stages of alteration by the elements are marked by the formation of carbonates and they then effervesce freely when treated with acid.

They occur characteristically in dikes, usually of but a few feet in width, but as previously mentioned, also in intrusive sheets, small laccoliths, etc. While they often cut the granite they are more apt to be found in the outer zone of rocks surrounding it and sporadic occurrences may be discovered a number of miles distant from the parent mass. The origin of these complementary dikes has been already discussed on pages 167 and 178.

Contact Phenomena. It is especially around great granite intrusions that the contact phenomena described on page 180 are seen in their greatest development and perfection. In the endomorphic form the granite may become a felsite or granite porphyry at the contact, or it may show a differentiated border zone (see page 165) and become so enriched in the dark silicates as to pass into a diorite or dolerite border facies, or, more rarely, on the other hand, be so poor in these as to present a marginal facies of aplite, quite like that seen in the complementary dikes. The first cases mentioned are purely textural modifications; the second are chemical and mineralogical. More rarely cases are known where granites have a border of pegmatite. With respect to exomorphism the changes described in the previous chapter, on account of the common occurrence of granites, are more frequently seen and have been more extensively studied in connection with them than with any other variety of igneous rock. Around the great granite batholiths these effects are often profound and far reaching, involving tracts of possibly several miles in width. Such areas are often of great interest and importance, not only from the geological standpoint, but because they are frequently the site of important ore deposits. If granite comes directly against sedimentary rocks with vertical contact and the latter show no evidence of metamorphism, it may be safely assumed that faulting or dislocation has brought them together.

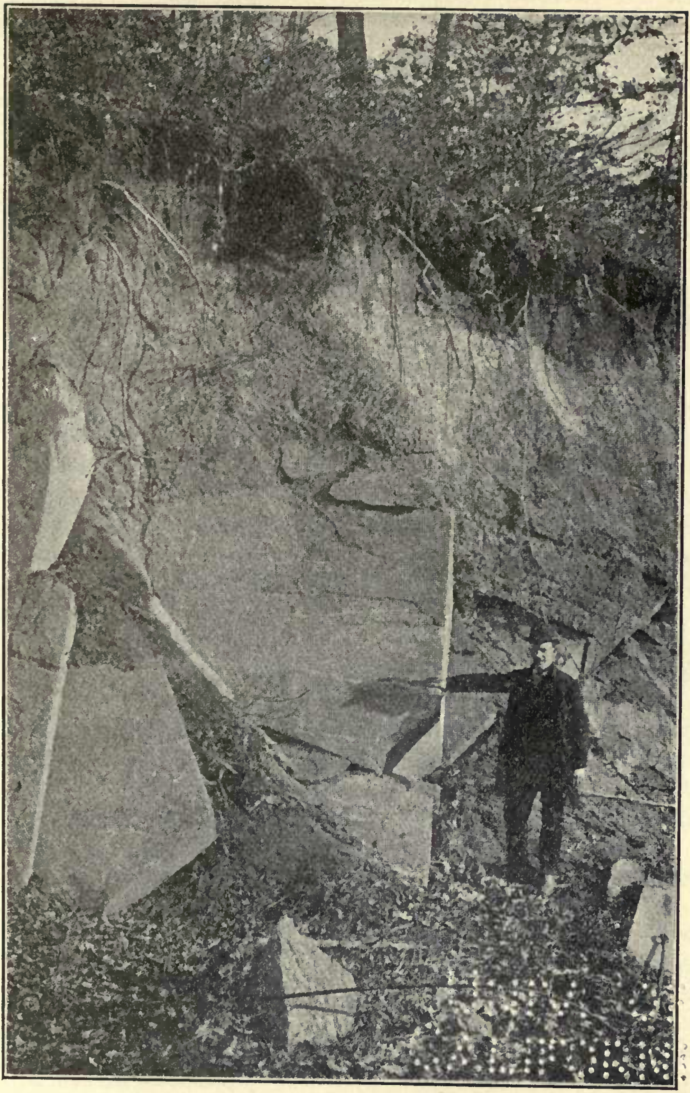
Weathering of Granite into Soil. Through the action of the atmosphere, of water, of heat and cold, granite breaks down into soil. In northern and in temperate regions, such as eastern North America, as Merrill has shown, this change is at first largely a mechanical disintegration and the resultant material differs in its general chemical composition but slightly from the original rock.

In appearance, however, as it changes granite may alter considerably. The mica tends to bleach and lighten, and ferrous compounds tend to become ferric and the iron oxide to leach out, staining the rock red to dark brown. At the same time its firm texture is lost and it becomes more or less friable and crumbly. Finally it falls into an angular gravel or sand, composed mainly of particles of quartz and feldspar, called *gruss*. See Plate 17.

From this stage as the change into soil becomes more complete, the most important process is the conversion of the feldspar into kaolin, according to the following reaction.

$$\begin{array}{ccccccccccc} \text{Orthoclase} & & \text{Water} & & \text{Carb.diox.} & & \text{Clay} & & \text{Quartz} & & \text{Potas. Carb.} \\ 2KAlSi_3O_8 & + & 2\,H_2O & + & CO_2 & = & H_4Al_2Si_2O_9 & + & 4\,SiO_2 & + & K_2CO_3 \end{array}$$

This reaction begins as soon as the rock is exposed; it has only partially taken place when the rock crumbles, but



GNEISSOID GRANITE, THROUGH WEATHERING, PASSING FROM FIRM ROCK BELOW INTO ALTERED ROCK AND SOIL ABOVE.

(Merrill, Bulletin Geological Society of America.)

after that goes on slowly but steadily until the feldspar is eventually wholly changed into clay. As a result, a soil consisting of a mixture of clay and quartz sand, stained reddish or yellowish by the iron compounds, is formed. Such a soil is called a *loam.* Usually the process is not entirely complete and the soil contains more or less small particles of feldspar undergoing alteration. This has an important bearing on the self-renewal of its fertility.

This reaction is one of the most important that takes place in the great laboratory of Nature, for by means of it, not only is the solid rock converted into soil, but one of the most essential of plant foods, the potash, is converted into soluble form in which it can be assimilated. At the same time the other essentials of plant food, the silica, magnesia, lime, etc., are also unlocked from the rocks and rendered available. Thus by their aid plant life is able to grow and produce from water, carbon, dioxide, etc., those substances upon which all animal life ultimately depends.

In tropical regions the decay of granite gives rise to a red or yellow-brown ferrugineous earth to which the name of *laterite* is given. It has been shown to consist of a mixture of quartz sand with hydrargillite, a clay-like substance with the composition $Al(OH)_3$, colored by iron oxides. But the name has also been applied in India to soils formed from the basalts of the great Deccan plateaux mentioned later.

In tropical deserts the surface of granites becomes coated by a brownish or black skin, sometimes with a luster like varnish, due to the alteration of the iron-bearing components and the formation of iron and manganese compounds. This also occurs with other kinds of rocks as well.

Occurrence of Granites. Granite is one of the most common and widely occurring of igneous rocks, and plays a prominent rôle in the formation of the continental masses. In the form of great stocks and batholiths it forms the central core of many of the great mountain ranges and is revealed by later erosion. In those parts of the earth's surface which have been subjected to repeated disturbances of the crust and profound erosion granites are common rocks. Thus great stocks of different ages of intrusion are found in eastern Canada, in New England and generally along the region of the Piedmont plateau from southern New York into Georgia. They occur again in Missouri, Wisconsin, etc., in isolated areas, but in general, until the Rocky Mountains region is approached, the central states, which compose the Mississippi Valley, being covered with stratified rocks, are devoid of them, though it may be inferred by analogy that they form a large part of the basement on which these later rocks lie. In the Rocky Mountains and in the far western states they are of importance. Likewise in Europe, in western and southern England, in Ireland and Scotland, in various places in France and Germany and in the Alps they are of common occurrence and their exposures form considerable areas. Such a list of occurrences might be almost indefinitely extended but enough has been said to show their importance and wide distribution.

SYENITE.

Composition. Syenites are granular rocks composed chiefly of feldspars. They differ from granites in that they contain no quartz or only a negligible quantity. They may consist entirely of feldspar, but usually more or less hornblende, mica or pyroxene is present. These however are subordinate in amount to the feldspar, since if they are equal to or exceed it, the rock becomes a diorite. If the rock is fairly coarse-grained, occasional particles of magnetite and other minerals may be seen, but these are only accessory and not of the importance of the ones mentioned. Occasional minerals which produce varieties will be mentioned presently.

In strict petrographic classification founded on microscopic examination a distinction is made in these rocks based upon the kind of feldspar. If the latter is predominantly an alkalic feldspar, without lime, the rock is called a syenite, as above, but if it is a lime-soda feldspar or plagioclase the rock is termed a *diorite* without reference to the quantity of dark minerals present. This distinction, however, cannot, except in certain exceptional cases, be carried out by megascopic examination and therefore no attempt is made to separate them in this work.

From what has been said it may be seen that the mineral composition of syenite may vary considerably; there may be a mixture of feldspars present or only one kind, either alkalic or lime-sodic, and there may be variations among the ferromagnesian minerals. According to the predominant kind of the latter, the rock is spoken of as hornblende syenite, mica syenite or augite syenite. All of these are here treated under the general heading of syenite, but in two cases the rock may have a particular mineral composition which makes it of especial interest and therefore deserving of separate description. Generally these two varieties may be identified by observing with care the special features which they present and which are described beyond, otherwise they cannot be distinguished and must be classed in the general group of syenites. These two are as follows: (A) the rock contains in addition to the feldspars and other minerals a notable amount of nephelite or this and its congener sodalite; (B) the rock consists entirely, or very nearly so, of soda-lime feldspar (labradorite). We may then divide the group of syenites as follows:

a. *Syenite,* in general or common syenite consisting chiefly of feldspars, without quartz.

b. *Nephelite Syenite,* consisting chiefly of alkalic feldspars with nephelite.

c. *Anorthosite,* consisting almost wholly of labradorite.

Properties of Syenite. The *texture* of syenites is usually even granular, but sometimes a tendency may be noticed for the feldspar to assume a flattened tabular form like that of a book, its cross sections on the rock surface are then elongated and often arranged more or less parallel, an arrangement which is thought to be due to movements of the fluid mass during crystallization. This variety of texture occurs practically only when the feldspars are of the alkalic variety. Porphyritic varieties also occur as in granite and these grade into syenite porphyry. The *color* is variable like that of granites; white to pink or red, or gray or yellow tones are common, gray especially so. The *specific gravity* varies with the minerals and their proportions; it may extend from 2.6–2.8. In a tendency to *miarolitic structure*, in *jointing*, in erosion forms, in *alteration* into soil, *inclusions*, and in *contact metamorphism*, etc., what has been said in regard to granite, applies also to syenites and need not be repeated. They are also accompanied by pegmatite dikes, but these are not so common nor so well known as the granite pegmatites. They also often yield a great variety of minerals.

Chemical Composition. Chemically, the syenites are distinguished from the granites by a lesser amount of silica, which accounts for the absence of the quartz; in other respects they resemble them. These characters may be seen in the following table of analyses.

ANALYSES OF SYENITES.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total.
I	60.7	19.6	1.5	3.0	0.8	2.3	4.9	5.9	0.3	0.6	99.6
II	60.2	20.4	1.7	1.9	1.0	2.0	6.3	6.1	0.3	0.4	100.3
III	61.6	15.1	2.0	2.2	3.7	4.6	4.3	4.5	0.7	1.0	99.7
IV	62.5	16.5	2.4	2.0	1.9	4.2	4.4	4.6	0.6	1.3	100.4

I, Belknap Mountains, New Hampshire; II, Fourche Mountain, Arkansas; III, Little Belt Mountains, Montana; IV, Plauen by Dresden, Germany. Xyo = Small amounts of other oxides.

Occurrence of Syenites. Syenites are not very common rocks, and, while they sometimes occur in independent masses, they are very apt to be connected with larger bodies of granite, which by the diminishing of quartz passes into syenite. In the United States they occur in several places in New England, at Mount Ascutney, in the White Mountains and adjacent region, on the coast north of Boston, also in Arkansas, in Montana and in a number of other localities. They are found in several places in Germany and in the Alps. An important area of them exists in South Norway. In comparison with the great batholiths and stocks of granite, distributed so generally in the continental masses, they are, geologically speaking, of relatively small importance.

Uses of Syenite. For all constructional and other commercial uses syenite has the same value as granite. On account of its relative rarity, compared with the latter rock, it is however little used. Its crushing strength is equal to that of granite and from experiments by J. F. Williams on syenite from Arkansas it may be even greater. Its weight per cubic foot is about the same. The absence of the quartz, which is harder than feldspar, should make it an easier stone to dress and polish, and practically it resists weathering as well, if not better. The absence of the quartz makes it also a better stone in resisting the heat of fires (compare granite, page 209) and it would be in consequence a more advantageous material for building in our large cities. If these advantages over granite were more generally understood it is probable that the accessible occurrences in New England would be more extensively exploited. The beautiful dark gray syenite of South Norway with pearly blue reflections is considerably used in northern Europe as an ornamental stone.

Nephelite Syenite. This variety is distinguished by the fact that in addition to the feldspars, which are almost wholly alkalic in composition, a considerable amount of nephelite is present. This mineral is sometimes flesh-colored but usually it is smoky gray. In its lack of good cleavage and oily, greasy luster it resembles quartz, but can be readily distinguished from it by the gelatinization test (page 115). It is generally present in formless grains mixed with the feldspars, but sometimes shows the outlines of a crystal form. It is apt to be accompanied by sodalite, which is often of a bright blue color, in grains or, if the rock is very coarse-grained, in lumps and masses; if it is thus present it is useful in aiding to distinguish this rock from common syenite. Nosean and cancrinite may also be present. Mica (lepidomelane), hornblende (arfvedsonite) and pyroxene (ægirite) are usually present in variable amounts, in plates, grains or prisms, of a black color, and containing considerable soda and iron. The presence of soda in the minerals of this rock is readily understood from a consideration of the chemical analyses, given beyond, which show the composition of the magma from which they crystallized.

The *color* of nephelite syenites is variable but commonly gray. The *texture* is granular, sometimes rather porphyritic. The book-shape of the feldspars mentioned above is common. The rock is liable to contain many accessory minerals but usually only in microscopic sizes; some of these are of especial interest on account of the rare earths they contain. It is also prone to exhibit in places great variations of the constituent minerals giving rise to different facies. Many of these varieties have received special names. Usually it is cut by *complementary dikes* and these are of a different character from those found associated with granites and common syenites; one is a pale brown or pink felsite, another a bright to dark green rock called *tinguaite* which owes its color to microscopic needles of ægirite; it usually contains nephelite and gelatinizes with acid. The complementary lamprophyres to these are heavy dark rocks of basaltic aspect often showing distinct to large phenocrysts of biotite, augite or hornblende; they are particular varieties of melaphyre (basalt-porphyry).

The chemical composition is illustrated in the two following analyses of nephelite syenites.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total.
I	58.8	22.5	1.5	1.0	0.2	0.7	9.6	4.9	1.0	0.3	100.5
II	53.1	21.2	1.9	2.0	0.3	3.3	6.9	8.4	1.4	2.0	100.5

I, Salem Neck, Mass.; II, Magnet Cove, Arkansas. XyO, small quantities of various oxides.

It will be seen that the most striking thing in respect to these magmas are the high amounts of alumina and alkalies, with moderate silica. It is this which causes the formation of nephelite ($Na_2O . Al_2O_3 . 2\,SiO_2$) rather than albite ($Na_2O . Al_2O_3 . 6\,SiO_2$), there being not enough silica to convert all the alumina and alkalies into feldspar. From this it may be seen that free quartz and nephelite cannot crystallize from the same magma; the silica would convert the nephelite into albite, and therefore these two minerals are not found in the same rock. Sometimes nosean is present; cancrinite may also occur, and of the associated minerals zircon is perhaps the most characteristic. In this connection the description of the feldspathoid group in the part dealing with minerals should be read.

Pegmatite dikes occur in connection with nephelite syenites and those of South Norway and Greenland are especially interesting for the great variety of minerals, many of them composed in part of the rarer elements, which they have afforded.

Nephelite syenites usually occur in rather small stocks or large dikes; relatively large areas of them are known in only a few places, Greenland, South Norway and Lapland. They are of rare occurrence and geologically are of small importance compared with granites, gabbros and diorites. In the United States they are found at Litchfield, Maine; Red Hill, New Hampshire; Salem, Massachusetts; Beemerville, New Jersey; Magnet Cove, Arkansas; Cripple Creek, Colorado; in western Texas and a few other localities. In Canada, at Montreal; Dungannon, Ontario; Ice River, British Columbia. Noted localities for these rocks and their associated minerals in Europe are in South Norway; Alnö Island, Sweden, Kola Peninsula and Miask, Ural Mountains, Russia; Foya, Portugal and Ditrö, Transylvania. The rock is too uncommon to be of commercial importance but makes an excellent building stone where it occurs. That in the neighborhood of Magnet Cove, Arkansas, has been thus used.

Anorthosite. This rock is composed wholly, or nearly so, of a soda-lime feldspar, usually the variety described as labradorite. Sometimes small quantities of a ferromagnesian mineral, pyroxene, is sprinkled through it in grains and specks, or small masses of magnetite or some other iron ore can be seen. This simple mineral composition makes it resemble in the hand specimen, especially when the grain is rather fine and the colors light, both marble and quartzite, also rocks consisting of a single mineral. From the former it is easily told by its superior hardness, since the feldspar cannot be scratched by the knife, while marble is easily cut or scratched, and from the latter by the cleavage of the crystal grains which can usually be easily seen with a lens. While these characters help to distinguish the rock, its identification can only be made certain by the determination of the kind of feldspar present; otherwise it can merely be referred to the general group of syenites. This can only be done in the field when the cleavage surfaces of the feldspars are sufficiently large to permit one to see on them the characteristic twinning striations of plagioclase (see page 38). In the laboratory the feldspar can be identified by blowpipe and chemical tests.

The *color* of the rock is normally white, and this is sometimes seen, but generally it is colored yellowish to brown, or, more commonly, some shade of gray, light gray, blue or smoky to dark gray and almost black. The very dark exotic color is due to an included pigment, perhaps ilmenite dust, but it is notable that where these rocks have been subjected to orogenic pressure, and especially when they have been sheared and granulated and have assumed gneissoid structure, the dark color tends to disappear and they become lighter. The chemical composition is practically that of a labradorite feldspar (Anal. IV, page 43).

Mineralogically, the anorthosites are related to the gabbros, for they contain the same kind of feldspar and often, as stated above, there is more or less pyroxene; if this latter increases in amount, passages into gabbro may occur; and in gabbros, phases poor in pyroxene, and thus transitional to anorthosite, are found. Geologically, however, they occur quite independently of gabbros. They are not common rocks, so far as the number of occurrences is concerned, but are of importance from the large and sometimes vast masses which they form, notably in Canada and Norway. They are found in Canada in separate areas from the west coast of Newfoundland and the east coast of Labrador down through Quebec into eastern Ontario. One of these areas drained by the Saguenay River covers nearly 6000 square miles while one near Montreal comprises about 1000 square miles.

Another region is in the Adirondack Mountains in northern New York state, which is in large part composed of this rock. Small occurrences of a nearly related type are found also in the White Mountains, New Hampshire. It is found again in considerable masses in Minnesota on the Lake Superior coast.

In Europe, anorthosite occurs in Norway in large areas on the west coast at Bergen, at Ekersund and on the Sognfiord. It is also found in Volhynia in Russia.

The labradorite of this rock sometimes shows a beautiful opalescent play of colors, especially a deep blue. Cleavage pieces from the coarse and massive rock of the coast of Labrador have long been known and cut as ornamental stones. Similar material comes from near Zitomir in Volhynia.

Corundum Syenite. In all the different varieties of syenite described above, instances have been found in which the rock contains, in addition to the usual constituents, a notable amount of corundum. The appearance of this mineral is due to the fact that the magma contains more alumina than the alkalies and lime present can turn into feldspars and feldspathoids, and this excess is forced to crystallize out as corundum (Al_2O_3), just as in granites the excess of silica is compelled to form quartz (SiO_2). The mineral occurs in crystals, either hexagonal prisms or barrel-shaped, or in grains and lumps, and is usually of a gray color. It is easily identified by its excessive hardness.

Such occurrences have been found in central Montana in common syenite; in the counties of Renfrew, Hastings and others in Ontario, Canada, in syenite and nephelite syenite; these rocks have been traced in a belt a distance of over a hundred miles; it occurs in a similar manner in the Ural Mountains and in Coimbatore district, India. Anorthosites containing corundum are known from Clay County, North Carolina; Lanark County, Ontario, and from the Ural Mountains. Some of these occurrences, notably the ones in Canada, are of economic value as a source of this valuable abrasive. Corundum also occurs in other kinds of igneous rocks as mentioned under dunite.

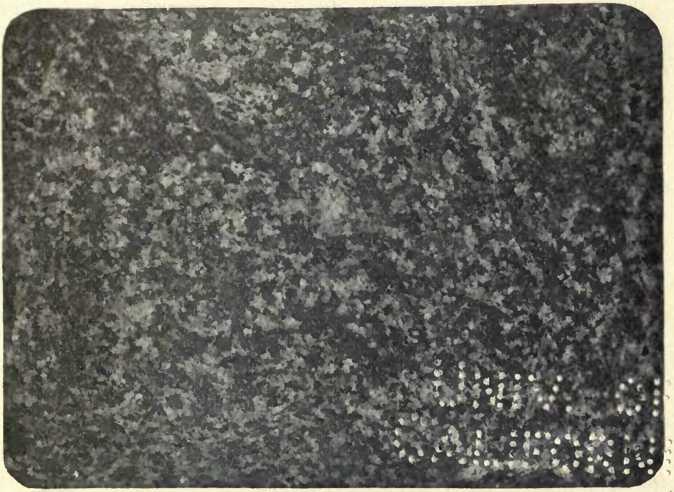
DIORITE.

Composition. The diorites are granular igneous rocks composed of hornblende and feldspar of any kind, in which the amount of hornblende equals or exceeds the amount of feldspar. Usually more or less iron ore in fine grains can be seen, and very often considerable biotite is present in shining flakes, with sometimes a bronzy luster. The hornblende is usually black, sometimes dark green, and, while often in bladed or prismatic forms, it is also often in short thick crystals or grains and sometimes in small masses of them and of biotite separated by the light-colored feldspar. For its recognition and distinction from pyroxene see page 66. While any kind of feldspar may be present, in the great majority of cases,

PLATE 18.

A. ORBICULAR DIORITE, CORSICA.

B. DIORITE.



C. DIORITE, COMMON TYPE.

as learned from microscopical studies, it is a soda-lime variety, containing considerable lime. This latter point however can rarely be determined on the hand specimens because the rock is not often coarse grained enough to permit the recognition of twinning striations on their cleavage surfaces. It is not uncommon for some quartz to be present and this can sometimes be identified with the lens.

While the rocks determined as diorites by this megascopic classification will correspond in a general way with the greater part of the diorites of the more strict classifications founded on microscopic and chemical methods they also include some less common rocks which, for one reason or another, have been given various names by petrographers.

General Properties. The *color* of diorites is dark-gray or greenish, running into almost black in some varieties. It results from the color of the hornblende and the proportion of this to feldspar. The different varieties are due to the color, coarseness of grain, etc. The *texture* of the rock is the granular one. The porphyritic texture, while not unknown, is far less common than in granite. Sometimes the black hornblende prisms are distinct enough to produce an impression of porphyritic texture which is dispelled as soon as one compares the average size of the crystal grains. Orbicular structures are known to occur. A rock from Corsica exhibiting it has been used somewhat as an ornamental stone; it is illustrated on Plate 18. Miarolitic cavities occur as in granite; they are often masked by being filled with calcite. Pegmatite dikes also occur and the minerals are somewhat different from those in the granites. Fluidal or somewhat parallel arrangements of the component minerals are not uncommonly seen, and these produce tendencies to gneissoid structure. Diorites are also frequently cut by complementary dikes, of much the same general appearance as those in granites, or these are found in their immediate neighborhood in dikes and sheets. Thus they may be traversed by light-colored aplites and felsites and by dark, heavy, basaltic traps.

Their jointing is like that described for granites.

Chemical Composition. This varies considerably with the relative amounts of feldspar and hornblende, with the particular varieties of these two which are present, and is also somewhat influenced by the accessory minerals which may occur. The following table illustrates this and it shows also how the increase of lime, iron and magnesia over the proportions of these oxides in granites and syenites, causes the increase in the amount of hornblende.

ANALYSES OF DIORITES.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total.
I	55.1	20.2	1.5	4.3	1.8	7.0	4.3	2.8	1.1	1.7	99.8
II	58.0	18.0	2.5	4.6	3.6	6.2	3.6	2.1	0.9	1.2	100.7
III	47.1	18.1	3.0	8.5	7.3	6.6	2.4	2.8	3.6	0.5	99.9
IV	43.9	16.2	4.0	10.1	5.1	9.6	2.9	1.5	1.6	4.9	99.8

I, Diorite, Little Belt Mountains, Montana; II, Electric Peak, Yellowstone Park; III, Malvern Hills, England; IV, Belknap Mountains, New Hampshire. XyO = Small quantities of various oxides, TiO_2, MnO, etc.

Occurrence, Uses, Etc. While diorites in many places are found as independent intrusions, they are also very apt to be, on the one hand, connected with granites, on the other with gabbros, and usually these pass into each other. They also do not form such vast batholiths or stocks as the granites or the gabbros, and, especially as independent masses, are more liable to be found as small stocks, large dikes, etc. They have a very wide distribution and are found in all parts of the world where the older deeply-seated igneous rocks are laid bare by continued erosion. In the later formed mountain regions they are also found as stocks and dikes. What has been said of granites in this respect would be largely true of diorite. Owing to its dark color diorite is not so extensively used for architectural purposes as granite, though, so far as strength, durability and capacity for receiving a high polish is concerned, it would furnish in many places excellent material. It is somewhat heavier than granite, its specific gravity ranging from 2.8–3.1; at 3.0 a cubic foot of it would weigh about 187 pounds.

Relation to Other Rocks. As mentioned under its description as a rock mineral, pyroxene through metamorphic processes changes into hornblende. Generally this is accompanied in the rock by the production of schistosity as described under metamorphism and hornblende schist. The description of uralite should also be consulted. It sometimes happens that this change takes place in gabbro without causing the rock to lose its massive character or becoming schistose. In this case, if of sufficiently coarse grain to permit the recognition of the hornblende and feldspar, it would be classed as a diorite. If it can be proved that a diorite has been derived from gabbro, it may well be termed a *metadiorite* to indicate its secondary origin. Usually, however, the grain of such rocks is quite fine, too much so to permit the individual hornblende prisms to be definitely determined, and the rock would be classed under dolerite. They are very apt to have a green color and for this reason have been called *greenstones*. The green color is partly due to hornblende, partly to chlorite. These rocks are further mentioned under dolerite.

GABBRO.

Composition. The gabbros are granular igneous rocks consisting chiefly of pyroxene and feldspar of any kind, in which the amount of pyroxene equals or exceeds that of the feldspar. Usually more or less iron ore in black metallic-looking grains can be seen, and in some varieties considerable olivine may occur. This latter can sometimes be detected with the lens as yellowish or green grains. Careful inspection will often show occasional bronzy flakes of biotite. Of the two chief minerals the pyroxene is usually dark greenish when examined with the lens, often black to the eye alone, and sometimes it is of the variety diallage with a pronounced apparent cleavage in one direction, of a gray-green color and often almost micaceous appearance, at times somewhat brassy or semi-metallic in luster. A test with the knife point for cleavage shows at once its non-micaceous character. The feldspar in the great majority of cases is a soda-lime variety, generally labradorite, as may often be seen by the twinning striations on a cleavage surface. It is usually in formless masses or grains like the other minerals, but not unfrequently it has a tabular or book-like form and the sections on the rock face have an elongated shape. In this case the striations run parallel with the elongation. Sometimes the feldspar is fresh and glassy; in this case the two feldspar cleavages are good and the striations if visible are distinct; sometimes the feldspar is waxy in appearance, of a glimmering luster to dull, often with a bluish tone; in this case the cleavage is poor or even apparently wanting and striations cannot be seen. In the latter case the feldspar is more or less affected by alteration to other minerals as described on page 44.

A distinction is made by petrographers by which gabbros are divided into two groups, depending on the variety of pyroxene present. If this is the monoclinic, lime-bearing augite or diallage, the rock is called gabbro, if it is the orthorhombic hypersthene which is without lime the rock is called *norite*. This distinction cannot be made in megascopic determinations unless some of the pyroxene is extracted from the rock and tested chemically, hence the norites are here included under gabbro. A rarer type consists of plagioclase and olivine without pyroxene and is called *Troctolite*. Some rare rocks with alkalic feldspar are also here included under gabbro which are variously classified and named by petrographers.

General Properties. The *color* of gabbros is usually dark, dark gray or greenish to black; very rarely reddish. In some varieties in which diallage is the kind of pyroxene present and the grain is moderately coarse the rock is much lighter in tone and of a medium gray or greenish-gray. The same is true in many cases where the rock is more or less altered; compare with what is said of the feldspars above. The *texture* is granitoid or granular, sometimes with a porphyritic tendency from the elongation of the feldspars, but true porphyritic texture is very rare. Miarolitic cavities are much less frequent than in granite and syenite. Orbicular gabbro has been found in California. A fluidal or banded structure which is produced by drawn-out layers of varying composition and which simulates a gneissoid structure has been described from several localities, from the Hebrides, California and Minnesota. *Pegmatites* are also occasionally found in gabbros; they consist of the usual minerals of the rock. In South Norway the pneumatolytic processes attending the intrusion of gabbros have formed much scapolite and other minerals in the gabbro at its border and in dikes in the contact zone; of these minerals apatite is the most prominent and occurs sometimes in large masses. Complementary dikes, etc., occur in gabbro masses but are not perhaps so notable a feature as in the foregoing groups. In this connection what is said concerning peridotites may be consulted.

ANALYSES OF GABBRO.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total.
I	47.9	18.9	1.4	10.5	7.1	8.4	2.7	0.8	0.6	1.7	100.0
II	48.9	8.8	1.0	9.5	15.2	14.7	0.6	0.1	0.6	0.7	100.1
III	49.9	18.5.	2.1	8.4	5.8	9.7	2.6	0.7	1.0	1.4	100.1
IV	52.8	17.8	1.2	4.8	4.8	12.9	3.0	0.5	1.2	0.5	99.5
V	40.2	9.5	9.7	12.2	8.0	13.1	0.8	0.2	0.5	5.5	99.7

I, Adirondacks, New York State; II, Orange Grove, Maryland; III, Pigeon Point, Minnesota; IV, Band rich in feldspar, poor in pyroxene, Isle of Skye, Hebrides. V, Band rich in pyroxene, poor in feldspar, Isle of Skye. XyO = small quantities of various oxides, chiefly TiO_2.

Chemical Composition. The gabbros, as a rule, contain larger amounts of lime, iron and magnesia, and less of silica and alkalies than any of the previously described rocks as may be seen from the table annexed.

Analyses IV and V show how the chemical composition of the banded gabbros varies in the different streaks with corresponding variation in mineral contents.

Occurrence. Gabbros are widely distributed and common rocks. They are found as large stocks and bathyliths and in dikes in the older rock complexes, similarly to granite. They are also found as stocks and necks of old volcanoes cutting the stratified beds of the younger mountain regions. In these they may also be found as thick intrusive sheets. Gabbros have been held to occur also as forming the central portion of thick extrusive sheets, as in the Hebrides, in Sweden and in the Lake Superior region. If this is the case it is due to the low freezing point of the magma, its liquidity and ready crystallization.

In the United States, gabbros are found in many places in New England, as in the White Mountains. They are found in the Adirondacks and at Cortlandt on the Hudson River in New York State, in Maryland, etc.

They occur in the Lake Superior region and elsewhere in Minnesota and in various places in the Rocky Mountains and in California. They are extensively distributed in Europe, in southern England, in northern Scotland, especially on the islands of the Hebrides, in Norway and Sweden and in Germany. They are in fact almost as widely known as granites though they do not form, as a rule, such large masses.

Alteration of Gabbro. It is common to find that where gabbro massives occur in the older rock complexes and in folded mountain ranges that they are surrounded by a mantle of hornblende schist into which the gabbro gradually passes, by transitional phases. The origin of this is the pressure, shearing and other metamorphic agencies brought about by the orogenic processes, as mentioned under metamorphism, hornblende, diorite, etc., which have acted upon the pyroxene of the gabbro converting it into hornblende and producing the schistose structure. It may happen through pressure and shearing that a schistose or, perhaps better, a gneissoid structure may be induced in the gabbro without change of the pyroxene to hornblende and we would have in this case a gabbro-gneiss or gabbro-schist produced, but generally the change to hornblende occurs. If olivine is present it also forms amphibole. Very often garnet appears as a new mineral resulting from the process. While the change to hornblende is usually accompanied by the assumption of a more or less pronounced gneissoid or schistose structure, this is not always the case; the rock sometimes retains a massive granular character and, if its constituent feldspar and hornblende can be recognized, it would be classed as a diorite, as mentioned under that rock. In another mode of alteration of gabbros the feldspar is changed into a substance called saussurite, which was formerly thought to be a distinct mineral, but which the microscope has shown to be a mixture of albite, zoisite and other minerals. The feldspar, or rather that which replaces it, has no cleavage and is waxy looking. The pyroxene is changed to hornblende, which tends to have a bright to grass-green color and is the variety called smaragdite. Other minerals are also formed, but megascopically the waxy-looking saussurite and green hornblende predominate. This may take place without formation of schistose structure and it seems probable that in this case the alteration is due more to the chemical and less to the dynamic agencies of metamorphism. Such rocks have been called saussurite-gabbro.

In the process of weathering through the agencies of the atmosphere, gabbros give rise to clay soils deeply colored by the oxides of iron and mingled with fragments of still undecomposed minerals.

Iron and Other Ore Deposits. There are frequently found in large gabbro intrusions masses of iron ore, sometimes consisting of magnetite, but generally of ilmenite or mixtures of the two. Usually these are more or less mingled with the minerals of the gabbro itself, especially pyroxene and olivine. The character of the occurrences, their lack of definite form and the manner in which they gradually shade into the normal gabbro, show that they are only a phase of the rock in which the iron ore, usually scattered through it in small grains, is here locally concentrated in great abundance. Such ore deposits are sometimes found at the border of the intrusion, though often scattered in masses through it or at the center. They are known in many places, in the Adirondacks, in northern Minnesota, in Canada, Norway, Sweden and elsewhere. If titaniferous iron ores could be successfully smelted, such deposits would undoubtedly be in many cases of great value.

In other cases sulphide ores are developed in gabbro rocks in a similar manner. This is especially true of the sulphide of iron called pyrrhotite, which is often nickel-bearing and hence of great value as a source of this useful metal. In some places these deposits are accompanied by valuable amounts of copper in the form of chalcopyrite, copper-iron-pyrites, and it has been remarked that as the percentage of copper rises that of nickel falls. Such deposits in gabbros, or in rocks derived from them, are known and have been worked in Norway and Sweden, in Lancaster County, Penn., and at Sudbury, Ontario.

The origin of this kind of ore deposit in an igneous rock has been described on page 170.

Use of Gabbro. The gabbros are well suited for constructional work and architecture, but as a rule have not been extensively used, probably very largely on account of their dark color. In Sweden they have received considerable attention for monumental and other uses. In the United States they have been used for building in the Lake Superior region, as at Duluth, and quarries of them at

Keeseville in the Adirondacks and in Vergennes, Vermont, have been worked. They take a high polish, are sufficiently durable and much easier to work than granite.

DOLERITE.

Definition and Minerals. The dolerites, as already explained in the section on classification, comprise those forms of diorite and gabbro in which, generally on account of increasing fineness of grain, the hornblende and pyroxene cannot be safely determined or distinguished from one another, although the eye or lens clearly sees that the rock is composed of feldspar mingled with an equal or greater amount of a ferromagnesian mineral.

This term as here used comprises not only the finer-grained diorites and gabbros but much also of what is termed " diabase " by the petrographers, as well as occasional rare rocks which need no mention here.

The feldspar, which is seen in larger or smaller grains and sometimes in more or less extended lath-shaped sections, is known from microscopic studies to be chiefly a soda-lime variety, though alkalic ones are also present to some extent and in some cases may replace the former; these distinctions cannot be made megascopically, and the plagioclase twinning can very rarely be seen on a cleavage face with the lens. The ferromagnesian minerals are in dark grains, perhaps short columnar; their cleavage surfaces can usually be seen but it cannot be said whether they are hornblende or pyroxene or a mixture of both. Sometimes olivine is also present and if its yellow-green grains can be detected it is very probable that pyroxene is the chief ferromagnesian mineral and not hornblende. In addition the lens will often show bronzy-looking flakes of biotite and metallic steel-like specks of iron oxide (magnetite or ilmenite) or sometimes brass-like crystals or grains of pyrite.

Color. Owing to the equal or predominant amount of ferromagnesian minerals, the color of these rocks is dark, medium or dark gray or greenish to black. As in most rocks the tone of color is best observed in viewing the rock at a little distance, so that the individual grains become indistinguishable and only their mass effect is seen.

General Properties. The *texture* of these rocks is granular to fine granular, they are sometimes porphyritic but these cases are described in the following section on the porphyries. Their *chemical composition,* in the great majority of cases, is similar to that of the diorites and gabbros already given and need not be repeated. They are heavy, the *specific gravity* being from 3.0–3.3. Their *jointing* is usually small cuboidal, wedge shaped or platy, often columnar and sometimes on a very large scale, though generally this structure is not so perfect as in the finer-grained basalts. It is most apt to occur in dikes, very thick intrusive sheets and in massive extrusive flows.

Occurrence. The dolerites do not occur in large stocks and bathyliths like the diorites and gabbros, though not infrequently these latter rocks pass into an endomorphic phase of dolerite at the margin of the intrusion. As intrusives they belong in the minor class, being found in dikes, small laccoliths and intrusive sheets, the latter often of great thickness, and in thick massive lava flows whose cooling has been slow.

In the eastern United States the most conspicuous examples are found in the intrusions and flows of " trap " of the Triassic formations stretching from Nova Scotia to Georgia. Through faulting and erosion they now give rise to definite topographic features, such as the ridges in Connecticut and the Palisades opposite New York City. Similar masses of these rocks are found in the Lake Superior region and in the great lava flows of the western United States. In all these occurrences they are associated with, and pass into, the denser forms of basalt. These larger occurrences of dolerite mostly contain pyroxene as the dominant ferromagnesian mineral and are largely the rock called "diabase" by petrographers, while cases where hornblende is dominant are mostly confined to dikes and smaller intrusions, especially in the older rocks.

Dolerites are also very common rocks in Great Britain in various localities, in dikes and intrusive sheets, and especially in the north of Scotland and Ireland where they are often extrusive and associated with denser basalts. They are in fact very common rocks in all parts of the world.

Relation to Other Rocks — Alteration. From what has been said it is easy to see that the dolerites are a class of rocks based largely on convenience. On the one hand they form a transition group, based on texture, between the diorites and gabbros and the dense basalts, and on the other they cannot depend wholly on texture, because relatively coarse-grained rocks may occur in which one cannot distinguish between hornblende and pyroxene and which must therefore be placed in this class.

The case might occur in which, instead of hornblende or pyroxene, biotite was the dominant mineral associated with the feldspar. Such rocks are not very common but sometimes occur, especially in dikes and sheets and with quite fine grain. They form the rocks called *mica trap* or minette, mentioned later under basalt.

The pyroxenic members of this group, by regional metamorphism, become converted into hornblende rocks, generally into hornblende schists, and both varieties by alteration may produce chlorite and pass into the so-called "greenstones." These alterations are quite similar to what has been described under gabbro. By weathering they become brownish and discolored and ultimately yield brown ferrugineous soils.

Uses. The rocks of this group are too dark and somber for general use in fine architectural or interior work, except for monumental purposes. The "trap" of the eastern states has been considerably employed in rough masonry, and where good natural joint faces can be used for wall surfaces, the brown weathering color gives pleasing effects. The toughness of the material, which the traps afford, has however caused it to be considerably used for block paving and the crushed stone for road making.

PERIDOTITE — PYROXENITE.

Composition. Under this group are comprised all of those granular igneous rocks composed of ferromagnesian minerals alone, or in which the amount of detectible feldspar is so small as to be entirely negligible as a component, and in which the mineral grains are sufficiently large to be determined. The chief minerals which form these rocks are olivine, pyroxene of both the augite and hypersthene varieties, and hornblende. These may occur alone or in various mixtures, and according to these the group has been sub-divided into types, some of the more prominent of which are as follows:

Pyroxenes and Olivine	Peridotite.
Hornblende and Olivine	Cortlandtite.
Olivine alone	Dunite.
Pyroxenes alone	Pyroxenite.
Hornblende alone	Hornblendite.

The first three, which contain olivine, are comprised under the general name of peridotites, from peridot, the French word for olivine. But all the different types, while they sometimes occur independently, also occur together, with transition forms grading into one another, and it is difficult, and sometimes impossible, to distinguish them megascopically and therefore they are best treated together as one general group and not as separate rocks.

Beside the minerals mentioned, a brown biotite sometimes occurs in these rocks, giving rise to the variety called *mica peridotite.* Additional accessory minerals, some of which are common and some confined to certain occurrences, are titanic iron ore, spinels, of which chromite is of importance, and garnet.

Texture. The texture is granitoid or granular; its appearance depends somewhat on the minerals present and their arrangement. When pyroxene or hornblende is the dominant mineral the grain is often very coarse and may exhibit large cleavage surfaces. Dunite is not apt to be coarse grained; it commonly has a sugar-granular texture like many aplites, sandstones, marbles, etc. Porphyritic texture is rare or wanting. A common texture is one in which the cleavage surfaces of the pyroxenes or hornblendes are seen to be spotted with grains of olivine included in the larger crystal. Such a spotting of the shining cleavage surfaces of one mineral by smaller included crystals of another, which have no crystal orientation, either with respect to one another or to their host, is called luster mottling and is known as the *poikilitic texture.* It is sometimes well exhibited in these rocks. The included crystals are of course older than their host.

Chemical Composition. This varies according to the minerals in the rocks but general characters are the very low silica, the small amount or virtual absence of alkalies and alumina, and the large quantities of iron and magnesia.

ANALYSES OF PERIDOTITES, ETC.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total.
I	40.1	7.8	7.3	8.6	23.7	6.5	1.2	0.5	4.0	0.6	100.3
II	43.9	1.6	8.9	2.6	27.3	6.3	0.5	...	8.7	0.3	100.1
III	53.2	1.9	1.4	7.9	20.8	13.1	0.1	0.1	1.0	0.5	100.0
IV	46.4	10.8	5.9	5.6	22.2	3.7	0.3	1.2	3.8	...	100.1
V	38.4	0.3	3.4	6.7	45.2	0.4	0.1	...	4.3	1.4	100.2

I, Peridotite, Devonshire, England; II, Peridotite, Baltimore County, Maryland; III, Pyroxenite, Oakwood, Maryland; IV, Hornblendite, Valbonne, Pyrenees; V, Dunite, Tulameen River, British Columbia. XyO = small quantities of other oxides.

Color. The color of these rocks ordinarily varies from dull green to black. The dunites, which are practically composed of the one mineral olivine, are at times much lighter. They may show various shades of light green, medium yellow and light brown, passing into one another, and from these through dull yellowish green into dark green. They may thus be exceptions to the general rule that ferromagnesian rocks are dark colored.

Occurrence. — Relation to Gabbro. The peridotites and allied rocks sometimes occur independently as dikes, sheets, laccoliths or small intrusive stocks. In this way, as small isolated occurrences they have been found cutting the Paleozoic rocks, usually in a more or less altered condition, at Syracuse and other localities in New York State, in Kentucky, in Arkansas and elsewhere. But generally speaking they are most liable to occur in connection with greater intrusions of gabbros. Sometimes they form phases of the gabbro mass, with transitions between the two; sometimes they cut the gabbros in dikes or are found in small intrusions in their neighborhood. This dependence upon the gabbros has led to their being held in such cases as products of differentiation of the gabbro magma in which they represent the lamprophyres of other rock groups. In this way a great number of occurrences are known in all parts of the world where gabbros are common rocks.

Dunites occur in masses intrusive in the gneisses of western North and South Carolina and Georgia. Associated with them are smaller amounts of other peridotites and pyroxenite. These occurrences are of importance on account of the deposits of corundum of commercial value associated with them. The mineral is thought to have formed in them in the same manner as described under syenite. Dunite also occurs in considerable masses in New Zealand, especially in the Dun Mountains, from which came the name. Pyroxenite and hornblendite are comparatively rare and of relatively small geologic importance.

Alteration. — Serpentine. The peridotites are extremely liable to alteration, so much so that unchanged occurrences are not at all usual. The most common form of alteration is that in which the olivine and other magnesian silicates are changed to serpentine.

This is illustrated by the following reactions:

$$\begin{array}{llll} \text{Olivine} & \text{Enstatite} & \text{Water} & \text{Serpentine} \\ Mg_2SiO_4 + & MgSiO_3 + & 2\,H_2O & = H_4Mg_3Si_2O_9 \\ 2\,Mg_2SiO_4 + & CO_2 & + 2\,H_2O & = H_4Mg_3Si_2O_9 + MgCO_3 \end{array}$$

$$3\,MgSiO_3 + 2\,H_2O = H_4Mg_3Si_2O_9 + SiO_2.$$

Other magnesian minerals such as talc are also formed by the alteration of these rocks, but that to serpentine is the most important. All stages of transition to pure serpentine occur, and studies which have been made in recent years show that a large part, perhaps the greater part, of the occurrences of this mineral are to be assigned to the alteration of rocks of this group.

The peridotites ultimately weather down into brown ferruginous soils which, on account of their lack of potash, do not favor vegetable growth and are therefore barren.

As a Source of Valuable Minerals. The magmas which form the peridotites usually carry small amounts of chromic oxide which often crystallizes with iron oxide to form the mineral chromite, $FeCr_2O_4$, one of the spinel group. It is often seen in dunite and usually forms small, black, pitchy-looking grains. Sometimes this mineral is concentrated in sufficient amount so that it becomes a useful ore, supplying the chromium used in the arts.

The olivine of these rocks has been found by analysis to contain a minute amount of nickel oxide; when they change to serpentine it sometimes happens that this nickel is concentrated in the form of nickel silicate, sometimes in amounts sufficient to form deposits of value as a source of this metal, as in Douglas County, Oregon, and in the Island of New Caledonia.

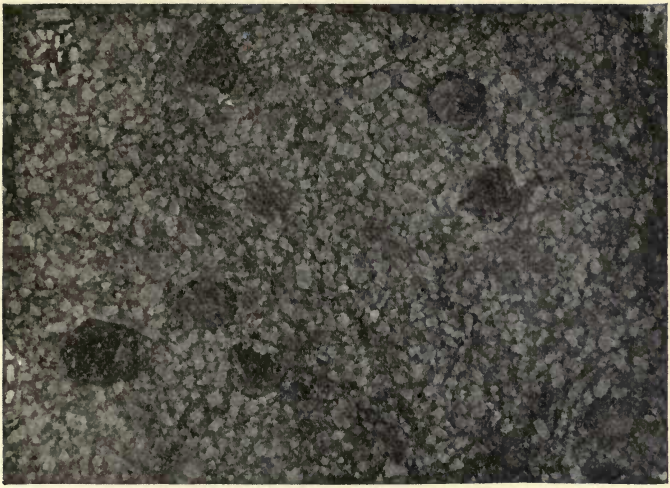
The peridotites, and to some extent their allies the gabbros, are also the source of platinum, which occurs in them as the native metal or as sperrylite $PtAs_2$; by the decay of the rock it is washed down and, like gold, concentrated in alluvial deposits. The precious garnet, pyrope, used as a gem, also comes from a decayed and serpentinized peridotite from Bohemia, South Africa, etc. Lastly, the diamonds of South Africa have their source in decayed and greatly altered peridotite rocks. This altered rock, which was originally a mica peridotite, is known as *kimberlite*, by the miners as " blue ground." Some have held that the carbon forming the diamonds was derived from the shales through which the magma passed, others hold that it was original in the magma and that the diamond is a true crystalline constituent of the igneous rock like any other of its accessory minerals.

PORPHYRIES.

Definition. As explained in the former section treating of the classification of porphyries, these rocks may be divided into two main groups; one in which, on account of its coarse texture, not only the phenocrysts but the grains of the groundmass can be determined or the determinable phenocrysts form so large a proportion of the rock that a good idea of its mineral composition can be obtained and the small amount of dense groundmass may be neglected, and a second group in which the amount of dense groundmass is large and the phenocrysts are not abundant enough to determine safely the mineral character of the rock. It is the first of these two groups which is described in this section, the one which we may call the group of determinable porphyries; the second group will be considered later in connection with the dense igneous rocks — the felsites and basalts — of which they form a porphyritic variety.

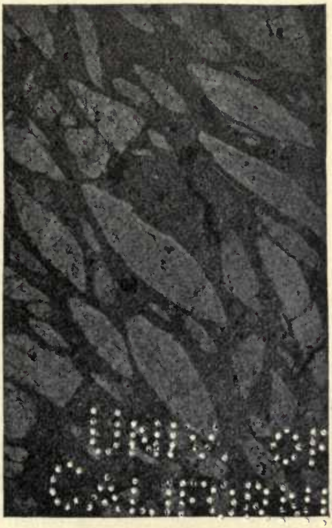
In this first group, porphyries are mainly confined to the feldspathic division of the igneous rocks, apparently for the reason that the magmas which furnish the ferro-

PLATE 19.



A. GRANITE-PORPHYRY, MONTANA.

B. SYENITE-PORPHYRY, MONTANA.



UNIV. OF
CALIFORN

C. SYENITE-PORPHYRY, NORWAY.

magnesian rocks have relatively so low a freezing point and crystallize so readily that they are not apt to form porphyries under conditions where the feldspathic rocks often do so readily. Thus granite porphyry is very common, while gabbro and peridotite porphyries are so rare as to be of no practical importance. In the group of dense igneous rocks porphyries of both divisions are common. The rocks to be treated then are granite porphyry, syenite porphyry and diorite or dolerite porphyry. There are so many points in which they are similar that they are best treated as a group.

Granite Porphyry. This consists of distinct phenocrysts of quartz and of feldspar in a granular groundmass of the same minerals whose grains can be determined as such, or one in which the abundance of the phenocrysts of quartz and feldspar give a distinct granite-like character to the rock and make the dense groundmass of less importance. Sometimes the rock consists of these minerals alone, or very nearly so, and sometimes biotite and hornblende are present, perhaps in considerable amount. The biotite and hornblende may be present separately or together, though hornblende alone is rare. They may occur as distinct phenocrysts, usually smaller than the quartz and especially the feldspar, and also in the groundmass, in which case the tiny specks of biotite are most easily detected.

When the groundmass is so coarse as to be equivalent to an ordinary granite it is customary to speak of the rock as porphyritic granite, as explained under granite.

Syenite Porphyry. This rock consists of distinct phenocrysts of feldspar in a groundmass, which, if determinable, must be made up mainly of grains of feldspar and with very little or no quartz. If the groundmass is not determinable the amount of phenocrysts must be large enough to give the rock a distinctly syenitic character. The ferromagnesian minerals, biotite, hornblende and pyroxene, while they may be absent or practically so, are usually present, either as phenocrysts, or in the groundmass, or both. They may occur in considerable amount, but must not equal or exceed the total amount of feldspar, or the rock becomes a diorite porphyry. They occur separately and together, but the combination of all three or of biotite and pyroxene is not so common as biotite and hornblende.

The rock defined above is that which corresponds to the common one of the three varieties of syenite described on page 219 and following, and represents it in porphyritic development. Anorthosite porphyry is unknown. Nephelite syenite porphyry is known but is a very rare rock.

In more exact classification based on microscopic research a distinction is made as to whether the feldspars are chiefly alkalic or mainly soda-lime feldspars, both phenocrysts and groundmass being considered together. In the latter case petrographers term the rock diorite porphyry and only apply the term of syenite porphyry where they are mainly alkalic. So far as the groundmass is concerned this distinction cannot be made by megascopic examination and but rarely, as described later, with the phenocrysts. Hence, just as in the case of syenite, both kinds are classed here together.

Diorite and Dolerite Porphyry. Diorite porphyry would be composed of phenocrysts of hornblende and feldspar, either separately or together, in a determinable groundmass of the same minerals, or if the groundmass is not determinable the diorite character must be clearly shown by the great abundance of the hornblende and feldspar phenocrysts. Also the total amount of hornblende must equal or exceed that of the feldspar. Some biotite may also be present, as well as iron ore grains.

Such rocks occur and it may be possible at times to determine them megascopically, but in the great majority of instances it will be found that, while the hornblende which is present in phenocrysts may be recognized, that which is present in the groundmass cannot. It can often be seen in these cases that the groundmass is composed of feldspar and a ferromagnesian mineral, either hornblende or pyroxene, but megascopically it is impossible to say which. In fact such groundmasses correspond to the definition and description of dolerite previously given and such rocks therefore are most conveniently called *dolerite porphyry*. The phenocrysts are either feldspar, hornblende, or pyroxene, or mixtures of them. The feldspar in these rocks is generally a variety of the soda-lime group, usually labradorite. By increase in the amount and density of the groundmass they pass insensibly into the basalt porphyries, or melaphyres, described later.

Phenocrysts of Porphyries. As the phenocrysts of porphyries have crystallized freely in the fluid magmas they generally show distinct crystal shapes, such as are described in the foregoing part devoted to the rock minerals. A few words in regard to their crystal habits may be added here. *Quartz*, as a phenocryst, tends to take the form shown in Fig. 43, but is usually spherical; the crystals may be a half inch in diameter but are usually much smaller, the size of coarse shot or peas; it is usually smoky in color. The *feldspars* tend to assume the forms shown by Figs. 5–7; they are often twins, Fig. 8; they are white, pink to red, or yellowish and gray; if feldspars of two colors are present and one of them is a reddish tone it is probably orthoclase, the other albite or a soda-lime feldspar. They not infrequently form very large phenocrysts, an inch or even more in length; the model-like feldspars seen in mineral cabinets often are the phenocrysts obtained from porphyries. *Hornblende* occurs in dark greenish or black prisms, usually elongated, and sometimes quite slender and with glittering cleavage surfaces if fresh; the terminal faces are poor or wanting; sometimes it is weathered out and only a rusty mass left in its place. *Pyroxene* is also dark green to black, in short, stout prisms, and commonly its cleavage and crystal faces lack the luster of hornblende. The method of distinguishing them has been already explained. Rusty spots also show the former presence of pyroxene, but less commonly than hornblende. In size both are apt to be small, compared with feldspar. *Biotite* as a phenocryst, is in six-sided tablets with fine basal cleavage, black to bronze-brown in color. In these rocks its crystals are apt to be small.

General Properties. The *chemical composition* of these porphyries is similar to that of the corresponding kinds of granular rocks previously given and need not be repeated. Their specific gravity and modes of alteration and conversion into soil are the same. The *jointing* depends largely on the mode of occurrence; it is apt to be platy or small cuboidal, or to form small parallelopipedons with acute angles, in the feldspathic porphyries of dikes and sheets, and larger blocks in the greater intrusions; the doleritic porphyries tend to columnar jointing.

Occurrence. The porphyries of this class are commonly found in the minor intrusions; in dikes, intrusive sheets and laccoliths, sometimes in volcanic necks. They are also not uncommon as marginal phases of intrusive stocks and bathyliths of granite, syenite, etc.; they here represent an endomorphic contact modification and in traversing areas of such rocks, if it is observed that they are becoming porphyries with finer grain, approach to the contact should be suspected. They may also occur in extrusive lava flows, especially if these are very thick and massive, but in this mode of occurrence they are generally replaced by the denser felsite and basalt porphyries described beyond.

These rocks are far too common to give any list of localities; they are everywhere found where erosion has exposed the older crystalline rocks and where igneous activity has displayed itself. Where larger stocks and intrusions have occurred they are especially apt to be present, sometimes cutting them as dikes, sometimes extending from them in apophyses, and sometimes in dikes, sheets, etc., as satellites grouped about them.

Perhaps the most notable instances of the occurrence of these rocks are to be found in the great laccoliths of the Rocky Mountains' region, in Colorado, Utah, Wyoming and Montana, which are generally composed of granite or syenite porphyries. Some of these masses are a mile in thickness by several in breadth, though often smaller. In these regions they often form powerful intruded sheets, several hundred feet in thickness. It is in the contact zones of these intrusions, especially with limestone, that a large proportion of the valuable ore deposits, such as the silver-lead ones, which have made these regions famous for their mining industries, are found. Thus to the western miner the word " porphyry " is always of suggestive significance.

Dense Igneous Rocks.

In the preceding groups of igneous rocks it is assumed that all the component grains of the rock, or those forming the greater part of it, can be determined and the mineral constitution safely established. In the present group it is assumed that the texture of all of the rock, or of the greater part of it, is so dense that this cannot be done. No definite line can be drawn between the two groups; in many cases, whether a given rock should belong to the one or the other, is largely a matter of opinion, dependent upon the experience of the observer, his knowledge of rocks and minerals, his power of observation, keenness of eyesight, and the excellence of his lens. In this respect we are also limited by our size; if we were ants, instead of men, who were studying rocks, it is probable that few would be placed in this group.

As has already been explained, under the section treating of the classification of igneous rocks, these dense varieties are divided into two groups, on the basis of color, into the dark to black *basalts* and the lighter colored *felsites;* each of these has a porphyritic subdivision. Of these the felsite will be considered first.

FELSITE AND FELSITE PORPHYRY.

The felsites include all those dense igneous rocks which are of stony texture and not evidently glassy, of all colors except dark gray, dark green or black, these latter belonging to basalts. They normally and commonly show light shades of color; white, which is not very common, light to medium gray, light pink or red to dark red, pale yellow or brown, purple or light green. With the lens it can be frequently seen that they consist of minute mineral grains, too small for determination, and the texture is then very fine granular. In other cases the grains may be entirely too fine to be seen; the rock has then a dense, horn-like or flinty aspect, appearing like a homogeneous substance. In this latter case it is very apt to have a smooth conchoidal fracture. In other cases, especially in surface lavas, the texture is more or less porous and the fracture surface of the rock rough and hackly, with a harsh feeling. A pronounced cellular or vesicular structure, common in basalts and in glassy rocks, and illustrated on Plate 8 is not very common in this group. The surface lavas not infrequently show fluidal bandings and streakings, more or less flat lenticular, and often curved or curled, due to flowage, and often clearly brought out on weathered surfaces, as illustrated on Plate 22.

The division of the dense igneous rocks into felsites and basalts is based on color, and not on mineral composition, since the latter cannot be determined. Nevertheless the felsites as classed above are, in general, feldspathic rocks, and they represent in dense form and often as lavas those magmas, which under different geologic and physical conditions, would have produced granites and syenites, while the basalts correspond to diorites, gabbros and dolerites, as already explained under classification.

In many cases, where these rocks are of medium gray or drab color, it is difficult to know whether to assign them to the felsites or basalts. This happens especially when they are very dense. In this case, if the rock be sharply examined with a good lens, it may be seen that many tiny chips and flakes, only partly formed and yet in the main a part of the mass, lie upon its surface, their thin edges separated from it by a flat underlying crack. It will be observed that their thin edges are very much lighter in color than that of the rock upon which they lie and are translucent to light; indeed in many cases they will appear practically white, even when the rock is a dark gray or stone color. This is a peculiarity of those dense rocks which are chiefly composed of feldspar and are, therefore, to be classed as felsites; it is not shown at all, or only in a very small degree, by the basalts. The reason for this is that, although they may be colored by a pigment, the feldspars are transparent to translucent minerals and a rock composed mostly of them is also megascopically translucent on thin edges, while one composed mostly of ferromagnesian mineral particles is not, since these minerals are either opaque, or practically so, from the megascopic standpoint. The same effect may be observed on the very thin edge of a flat chip broken from the rock. In case the rock is not so dense, but that the individual grains can be seen with the lens, if these are transparent or translucent with light colors, it may be assumed in general that they are mainly feldspar, the ferromagnesian mineral grains being mostly dark, dull, to opaque. Olivine, with its yellow-green color, however, is an exception and must not be confused with feldspar. It will also be noted that under a good lens the mineral grains, or many of them, appear much lighter in color than does the rock in its general effect to the eye.

These tests, while they cannot be held to be exact, will often prove of service in helping to decide, in doubtful cases, whether a rock belongs to the felsites or basalts, for the division between them, while based primarily on color, is due also to a mineralogical difference as well.

It is assumed in what has been said regarding these rocks that one is dealing with reasonably fresh, unaltered material, not those rocks which have been long exposed to atmospheric agencies and are weathered into dull ferrugineous material, or green masses of chlorite.

Varieties of Felsite. From the megascopic standpoint the different varieties of felsite which can be recognized are those which are due to color and texture alone; the petrographer by the use of the microscope on thin sections is, however, able to determine the different kinds of minerals, which form the minute grains, and to divide and classify these rocks on a mineralogical basis, just as was done with the coarse-grained rocks, whose grains could be seen and determined by the eye.

This is done on the consideration of whether the rock contains quartz or not, whether the predominant feldspar is alkalic or a soda-lime variety, or if it contains a feldspathoid, such as nephelite, in addition to the feldspar. According to this we have the following kinds recognized by petrographers.

Chief Component Minerals.	Rock Name.	Equivalent Coarse-Grained Rock in Petrographic Class.	Equivalent Coarse Rock in Field Class. of this Book.
Alkalic feldspars and quartz.	Rhyolite	Granite . . .	Granite.
Lime-soda feldspars and quartz.	Dacite	Quartz diorite .	Granite.
Alkalic feldspars, little or no quartz.	Trachyte	Syenite . . .	Syenite, mostly.
Soda-lime feldspars, little or no quartz.	Andesite	Diorite	Syenite and Diorite.
Alkalic feldspars and nephelite.	Phonolite	Nephelite Syenite	Nephelite Syenite.

A variety containing lime-soda feldspars and a feldspathoid is known, but is very rare. The ferromagnesian minerals are present in variable amounts and, according to the dominant one of these, we have such terms as *mica-trachyte, hornblende-dacite, augite-andesite,* etc., etc.

These are terms which are constantly seen in geological literature and in general it can be understood that the rock so designated has been subjected to microscopic study. They distinguish varieties of the felsites which cannot be accurately made without such study, but on the other hand the following points will serve in a rather vague and general way to indicate megascopically, to which of the above divisions a given felsite probably belongs. If the rock contains phenocrysts of free quartz, as mentioned later in the description of the porphyritic varieties of felsite, it almost certainly contains a considerable amount of quartz in the dense groundmass and is either a rhyolite or dacite; of these rhyolite is more common than dacite. If the rock on being tested yields gelatinous silica, according to the method recommended on page 115, it is almost certainly a phonolite. The distinction between rhyolite and dacite, and between trachyte and andesite, cannot be made megascopically, since it depends on the determination of the kind of feldspar, and in dense rocks this can only be done by optical means.

Felsite Porphyry or Leucophyre. While felsites occur which contain no porphyritical crystals it is much more common for them to contain phenocrysts. These may be very few, scattered and isolated, or they may be abundant. They may be quite evenly scattered, or they may be collected in groups. By increasing abundance, when they form half the bulk of the rock or more, they cause transitions into the group of determinable granular porphyries previously described. The phenocrysts may be salic, in which case they are *quartz* or *feldspar*, or they may be ferromagnesian, *biotite, hornblende* or *pyroxene.* For the appearance and properties of these phenocrysts reference may be had to the description of them in the former group of porphyries, page 245.

In the association of these phenocrysts, while all of the above minerals occur at times alone, there are apt to be two or more present. Quartz and feldspar with the others is not uncommon, if a dark mineral is associated with the quartz it is most apt to be biotite; hornblende is less common and pyroxene very rare. Feldspar and hornblende, pyroxene and feldspar are very common. In general feldspar is the most common phenocryst.

In naming these rocks the general term of *felsite porphyry* may be given to them or this may be contracted to *leucophyre,* from the Greek (λευκός — white) meaning light-colored porphyry.* If no mineral qualifier is used with this it is understood that the phenocrysts are of feldspar, since this is most general. If they are of quartz, biotite, hornblende, etc., we have as follows:

Quartz-felsite-porphyry or *quartz-leucophyre.*
Hornblende-felsite-porphyry or *hornblende-leucophyre.*
Biotite-felsite-porphyry or *biotite-leucophyre.*
Augite-felsite-porphyry or *augite-leucophyre.*
Hornblende feldspar-leucophyre.
Quartz-feldspar-leucophyre.

---

* As suggested in the "Quantitative Classification of Igneous Rocks." Messrs. Cross, Iddings, Pirsson and Washington, p. 184.

These examples are sufficient to show how mineral qualifiers may be used in designating the phenocrysts of these rocks, and how these may be combined, if desired, to give expression to considerable descriptive detail. Other examples will readily suggest themselves.

The same distinctions are made by petrographers among these rocks, as in the felsites proper, and as described above. Thus we find such terms in use as "rhyolite-porphyry," "mica-andesite-porphyry," "augite-trachyte-porphyry," etc., resulting from the study of thin sections and accurate determination of the different kinds of minerals.

General Properties. The *chemical composition* of felsites is variable, depending, like the subvarieties enumerated above, on the prevailing minerals. Some correspond with the analyses of granite already given; these contain free quartz; others are like the analyses of syenites and such must contain little or no quartz. If the amount of lime is small, the silica below 60 per cent, and the alkalies high the rock must be mostly composed of alkalic feldspar and probably nephelite is present. The *specific gravity* ranges from 2.4–2.65 and is usually lower than that of granite and syenite. The *jointing* is platy, or in small blocks; columnar structure also occurs, but is not so common nor so perfect as in basalts. In normal *weathering* to soil these rocks become discolored, brownish, reddish, etc. The ferromagnesian mineral generally disappears, leaving a rusty spot or cavity; the rock crumbles into débris, at first largely through mechanical disintegration. Finally the feldspars change to clay, as described under granite, and the change to soil is complete. Where hydrothermal action takes place, as in the vicinity of ore veins, they are often changed to soft clay-like masses consisting sometimes of clays, and sometimes of sericite, the fine scaly form of muscovite.

Occurrence. Felsites occur intrusively as dikes and sheets, and sometimes as the endomorphic contact facies of larger intrusive masses, whose main character is that of granite, granite-porphyry, syenite, etc. They indicate intrusions of magma into cold rocks, and when found in intrusions, these are usually relatively small, or narrow.

They are much more common extrusively, as lava flows and sheets, and they sometimes cover very large areas, many hundreds and even thousands of square miles in extent. In these cases, and especially in volcanic cones or their eroded remnants, they are usually interbedded with tuffs and breccias.

While it would be impossible to give any adequate list of actual occurrences it may be mentioned that felsites as intrusives occur extensively in eastern North America, among the older rocks in the Atlantic border states, along the eastern front of the Appalachian uplift; as extrusives they occur in Maine, in the White Mountains, in Pennsylvania and to the southward. They occur also in Wisconsin. Much more extensive in western America is their effusive occurrence throughout the whole of the Cordilleran tract, where they play an important rôle in the upbuilding of many of the ranges, and sometimes occupy large areas. Here all the different varieties are found, as for instance rhyolite in the Yellowstone Park, in Colorado and elsewhere; andesite in the lofty volcanoes of the Coast Ranges, and in those in South America, and in the eroded ones of the main chain of the Rocky Mountains; the rare variety phonolite is found at Cripple Creek, Colorado, and in the Black Hills of South Dakota.

The felsites are just as extensively found in other parts of the world. In Europe they are well distributed as effusive lavas. So in Great Britain they occur in northern Wales, in the Lake district of England, and in northern Ireland. These are the varieties called rhyolite and andesite. They are found in western Germany, in France, Italy, and in Hungary. Wherever volcanic outbreaks have taken place extensively, felsite lavas occur.

Felsites and felsite porphyries are often found, in the form of narrow dikes and sheets, traversing larger stocks or intrusions of coarse-grained rocks, such as granite, syenite, etc., or the rocks in their immediate vicinity. They are generally complementary in this case to dark basaltic dikes, mentioned later as lamprophyres, and have received special names from petrographers. Thus we have *bostonite* (allied to trachyte), *tinguaite* (allied to phonolite) and many others. Note in this connection paragraphs on complementary rocks, on aplite, and on lamprophyres.

BASALT AND BASALT-PORPHYRY.

The basalts include those dense igneous rocks, of very dark color, whose fabric is so fine that the constituent grains either cannot be perceived by the eye or with the lens, or, if seen, are too small to be recognized, and which are of stony but not of glassy texture. The color varies from grayish black or dark stone color, greenish or purplish black, to pure black. In the great majority of cases they do not show translucency on the edges of thin flakes as described under felsite. When not cellular, and very dense, they have a uniform dull, soft, almost velvety appearance, and do not show the horny, flinty, or greasy luster of many dense felsites.

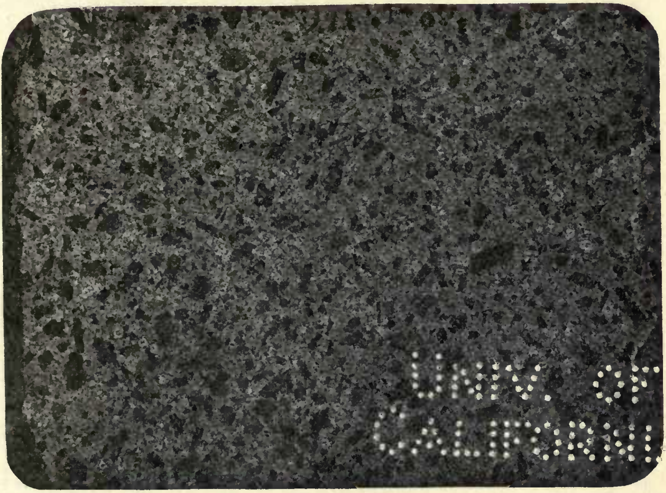
The study of thin sections of these rocks shows that in general they are composed of minute crystal grains of soda-lime feldspar — generally labradorite, — pyroxene and iron ore, very often with more or less olivine, and sometimes biotite or hornblende. In some cases nephelite or leucite may accompany the feldspar, or replace it, giving rise to varieties which have received special names. These varieties, although very interesting from the standpoint of theoretical petrography, are comparatively rare and relatively of small importance in a general geological way.

Being composed of the same minerals, these rocks represent, in dense form and generally as surface lavas, those magmas which, under different physical conditions, would have solidified as gabbros, peridotes, dolerites and (in part) diorites. A large part of the dolerites in fact are transition rocks between them and gabbros, as previously mentioned in the description of that rock, and instances may be found in the same rock mass where the gradation into dolerite may be seen.

Basalt Porphyry. While porphyritic varieties of basalt are not uncommon rocks it may be said in general, that this type of texture plays a far less important rôle in this

PLATE 20.

A. Labradorite-Porphyry.



UNIV. OF
CALIFORNIA

B. Augitophyre.

VARIETIES OF BASALT-PORPHYRY.

group than in the felsites previously described, owing probably to the low freezing point and easy crystallization of the magma. One exception to this, however, is in the presence of olivine, which is very apt to occur scattered through the basalt in transparent yellowish or bottle-green porphyritic grains, averaging about the size of moderately coarse shot. The mineral is so common (indeed at one time a rock was not considered a basalt unless it contained olivine) and produces in general so little of a striking porphyritic effect, that it is rather the custom to ignore it in this respect, and term such rocks olivine-basalt rather than olivine-basalt-porphyry.

The chief minerals as phenocrysts, when such occur, are feldspar and pyroxene; hornblende and mica are much less common. The feldspar is commonly labradorite; it occurs in elongate tabular forms, either singly, or in twinned groups. The pyroxene is the variety augite; it is black, sometimes shining, sometimes dull, and is in short thick prisms or prismoids, as illustrated under pyroxene. The hornblende is also black and has its usual shining and good cleavage. Biotite is in six-sided tablets.

These rocks would be named in accordance with the prevailing phenocryst, so for example *augite-basalt-porphyry*. Instead of the term basalt-porphyry the name *melaphyre*, meaning "black porphyry," may be used as more convenient * and we should then have *feldspar-melaphyre*, *augite-melaphyre*, *biotite-melaphyre*, etc.

General Properties of Basalt. The *chemical composition* of basalt varies with its mineral composition; in general it is of the same nature as that of gabbro previously given, as may be seen from the following analysis of one from California, which will serve as an example.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
51.9	15.3	3.1	3.6	8.7	7.4	3.3	2.5	2.5	1.7	= 100.0

The *specific gravity* is high, about 3.0 (2.9–3.1). The *jointing* is platy or columnar; the best examples indeed of

---

* Quantitative Classification of Igneous Rocks, p. 185.

this structure are found in basalt and many notable examples of it are found in all parts of the world, the Giants' Causeway on the north coast of Ireland being one of the best known. This structure is seen in Plate 11. Sometimes basalt on weathering develops a singular "pillow" structure by which there is formed spheroidal masses.

Varieties. In the dense non-porphyritic basalts there is little opportunity for variation, save that which is based on a change from the compact into the porous or cellular structure. This last is particularly common in surface lavas, especially in their upper portion, and has been illustrated on Plate 8. It is particularly in these basalts that the amygdaloidal structure occurs, also illustrated on the same plate. The minerals filling the cavities in basalt are commonly quartz, calcite or zeolites; among the latter minerals analcite, natrolite, stilbite and heulandite may be particularly mentioned. Such rocks are termed *amygdaloidal basalt.* In a number of places, and particularly in western America, basalts have been found as surface lavas which contain visible grains of quartz. One of the most noted of these is the basalt flow from the Cinder Cone, near Lassens Peak in northern California, which is filled with angular pieces of quartz of varying sizes. As many of these correspond in composition to gabbros and dolerites, the presence of the quartz in them appears anomalous, since magmas so low in silica, as may be seen by referring to the analyses of gabbro, would not be expected to develop free quartz on crystallizing. Some petrographers therefore think that these are fragments of quartz rock in the depths, which have been torn loose and distributed through the magma, while others regard them as a primary crystallization, produced under exceptional conditions of pressure and mineralizers. These rocks have been called *quartz-basalts.*

The porphyritic varieties have been described above, but it may be mentioned that a variety containing distinct and sometimes large crystals of labradorite feldspar has been called *labradorite-porphyry.* The greenish-black porphyry from Greece, employed by the ancients (porfido verde antico), is a somewhat altered example of this type. A variety containing rather large and distinct crystals of augite has been termed *augitophyre.*

The name *trap* has been used in a general way as a field term to designate the rocks called here basalts, and also dolerites. As thus employed it would mean any dark-colored, heavy, igneous rock of undetermined mineral composition. Thus the dolerites and basalts of the Newark formation along the Atlantic coast have been termed "Triassic traps;" the great effusives of western India are known as the "Deccan traps."

Lamprophyres. The ferromagnesian complementary rocks, occurring in dikes and sheets in or around stocks of granite, syenite, etc., and often called "trap" dikes, etc., belong for the most part under this heading of basalt. Their origin and relations have been discussed in the preceding part of this work and they have been mentioned again under granite. They are very apt to contain phenocrysts of the ferromagnesian minerals, olivine, augite, hornblende and biotite, either separately or together, and sometimes these phenocrysts are of very large size. These are embedded in a groundmass that is usually dense and basaltic. According to the variations in the minerals, as shown by the microscope, a large number of different types have been named by petrographers, distinctions which ordinarily cannot be made megascopically. For field work they may be treated simply as basalt-porphyries as described above, and termed augite melaphyre, biotite melaphyre, etc. It may be mentioned that biotite melaphyre is a rock which is frequently found in dikes with granite, and has been called *mica trap* or *minette.* A hornblende melaphyre occurs in the same way with many syenites and nephelite syenites; it has quite a wide distribution in New England and has been termed *camptonite.*

Olivine Nodules. It frequently happens that basalts, in addition to the ordinary crystals of olivine, contain yellowish, or green lumps, or nodules, made up of grains of this mineral. Grains of other minerals, such as pyroxene, spinel, etc., may be present in them. These lumps may vary in size from a pea to masses as large as one's fist, or even larger. They are generally rounded, but often distinctly angular in shape. Their origin is somewhat problematical; some hold that they are merely agglomerations of the earlier formed crystals in the liquid magma, while others regard them as fragments of rock (dunite) torn off below and brought up in it.

Exotic Minerals. Basalts sometimes contain unusual minerals, which do not appear in the ordinary rock, and whose origin in them must be ascribed to unusual conditions, or composition of the magma. The quartz basalt mentioned above is one of these. Another case is seen in the iron-bearing basalts of Greenland, which contain small to large masses of native iron, which is much like the iron found in meteorites. By the use of a solution of copper sulphate specks of native iron have been found in basalts from other places. The Greenland basalts also contain graphite. Corundum, in the form of sapphire, has also been found in basalts, and a dike in Montana has furnished a quantity of valuable gems. In this connection also, may be mentioned the occurrence in places of native copper, especially in the Lake Superior district, where the metal occurs in dolerites and basalts and in connection with them, in quantities which have made it one of the most important sources of the world's copper supply.

Weathering and Alteration. In many volcanic regions, where basalts have been subjected to exhalations of steam or to heated water, the minerals containing ferrous oxide, such as magnetite and olivine, become reddened through change to ferric oxide. Sometimes the olivines alone are reddened; in other cases the whole rock becomes deep red to reddish brown. Such rocks may be difficult to distinguish in the field from red felsites, and may even have to be classed with them. Sometimes, however, the association with other rocks, the retained form of phenocrysts, and the good amygdaloidal structure, rarely seen in the most common felsites, may help one to recognize the original character of the rock.

The normal weathering of basalt gives rise to chlorite, serpentine, and carbonates, with clay and iron ores; the rock often turns green and becomes soft when much chlorite is developed. In other cases it turns brown through oxidation and eventually falls away into brownish ferrugineous soil, to which various names are given, as *laterite* in India, *wacke* in Germany, etc. Sometimes from such deposits all but the hydroxides of iron and alumina are leached, forming one variety of the so-called *beauxite.*

Under processes of metamorphism the basalts act like the gabbros and dolerites previously described, and give rise to "greenstone" and to greenstone schists and amphibolite.

Occurrence of Basalt. As intrusive rocks, sheets, and especially dikes, of basalt of various types, both plain and porphyritic in texture, are so common in all regions where igneous rocks occur that they need no further mention. As extrusive lavas, in the form of flows and extended sheets, they are of much greater geological interest and importance. There is scarcely any volcanic region in the world which does not exhibit them in greater or lesser amount, and in some regions, as in the lava fields of the Columbia in western America, and in western India, they have been poured out in stupendous masses, so that tracts of country nearly 200,000 square miles in extent have been covered thousands of feet deep. A similar great field existed in northern Great Britain, and its remnants, portions yet saved from the eroding edge of the Atlantic, form in great part the northern British Isles.

Leucite Rocks. Basaltic rocks in which the feldspathoid minerals, nephelite or leucite, are present, either accompanying the feldspar or replacing it, while not common, have in certain regions a considerable local development. Ordinarily these minerals are in the groundmass, and only to be detected by the microscope, and such rocks in the field must be classed as regular basalts. In central Italy, however, the leucite rocks have a great development, and in many cases the leucite crystals appear as phenocrysts as large as peas, or larger at times, and are easily recognized. They are leucite-basalt-porphyries or leucite-melaphyre. For the properties of leucite its description under rock minerals should be consulted. According to the other minerals present, several different types of these rocks are distinguished and named. Some of them are so light colored they would be classed as varieties of felsites. Outside of Italy these leucite rocks are very rare, occurrences being known in the Rhine district, in central Montana, western Wyoming and a few other localities, but since the well-known lavas of Vesuvius are composed of them, they are mentioned here.

Glassy Rocks.

In the felsites and basalts the use of the microscope on thin sections would show in many cases that a certain amount of glass, uncrystallized and solidified magma, is present in them, acting as a cement to hold the mineral grains together. This cannot be detected megascopically, and under the term of glassy rocks, as here used, is meant only such as are entirely of glass, or if partly crystalline, those containing it in such amounts and in such circumstances, that it is visible and evident to the eye.

The conditions which will cause a magma to solidify as a glass are evidently those which are unfavorable to crystallization, extremely quick cooling in the first place, and probably to some extent the rapid loss of mineralizers in the second. This has been already discussed in connection with the texture of igneous rocks. These conditions are best realized when the magmas are poured out on the surface as effusive lavas, and just as we associate a coarse-textured, entirely crystalline, granular rock, such as granite, with an intrusive or deeply seated origin, so conversely we associate glassy rocks with an extrusive one. Indeed while it is true that dikes may sometimes show glassy selvages along the contact, when they have been intruded into cold rocks, or may indeed be wholly of glass when the exposure is near the original surface, as in recently denuded dikes in volcanic regions, this is so uncommon and so inconsiderable an affair, that in general we may regard the fact, that a rock is composed partly or wholly of evident glass, as a proof of its extrusive origin, that it was originally a surface lava, although it may have been buried under later formations.

Any of the different magmas, varying as to composition, may form glassy rocks if chilled with sufficient rapidity, but petrographical research has shown that, while glassy forms of the felsite lavas are common, those corresponding to basalt are much rarer and relatively of inconsiderable volume. The reason for this appears to be that the magmas, which furnish felsites, or the granite and syenite which correspond to them, have a relatively high freezing point, and as the magma cools down and approaches this, it becomes so enormously viscous that the free movement of molecules necessary for crystallization is prevented. This is due to the large amount of silica that such magmas contain, which has a strong effect in promoting viscosity. The presence of water in the magma tends to neutralize this, and to make the magma more fluid and thus to help crystallization, but when it is poured out on the surface the water is rapidly lost with increase in viscosity. On the other hand the basaltic magmas, or those corresponding to gabbro or diorite in part, which contain relatively low silica and high iron and magnesia, have a much lower freezing point and remain liquid as they approach it, thus permitting easy crystallization and the assumption of stony texture and appearance. Consequently those glasses, which have the highest percentage of silica and correspond to granite in composition, are the most common ones.

Classification of Glassy Rocks. As already stated in the classification of igneous rocks, we may divide the glassy rocks into two groups, one containing distinct crystals or phenocrysts embedded in a glass base, or porphyritic varieties in short, and second, those without distinct phenocrysts, consisting of either pure glass, or glass more or less filled with spherulites or lithophysae, as described later. The second group is again subdivided according to luster and structure. In accordance with this we have as follows:

Glass with few or no phenocrysts	*Obsidian,* strong bright vitreous luster.
	Pitchstone, dull pitchy or resinous luster.
	Perlite, apparently made of small spheroids.
	Pumice, cellular structure, glass froth.
Glass more or less filled with phenocrysts	*Vitrophyre,* glass porphyry.

Obsidian. This is pure, solid, natural glass, devoid of all apparent crystal grains, or nearly so. It has a bright luster like that of artificial glass. It usually has a jet-black color, but when the edges of thin chips are examined against the light it is generally seen to be transparent or translucent with a more or less smoky color, and it can be often observed with a lens that the coloring matter is more or less collected into fine parallel streaks, bands, or threads, as if drawn out in the flowage. Less commonly the glass is gray, or Indian red, or rich brown, and this is sometimes mixed with the black in bands and strings, which kneaded through it produce a marbled effect. The microscope shows the black glass as colorless and filled with tiny, black, dust-like particles; they are probably specks of magnetite, which represent the beginnings of crystallization, and diffused through the glass, they act as a pigment, coloring it black. In other cases they have been oxidized to hematite dust and the color is then red or brown.

Obsidian has a remarkable conchoidal fracture, illustrated in Figure 4, page 29, due to its homogeneity and lack of structure. It was this quality that made the substance so highly valued by primitive peoples, for it enabled them by chipping to work it into desired forms, knives, spearheads and other implements and weapons, while long, slender flakes possessed, for cutting purposes, knife-edges of razor-like keenness. The ancient Mexicans were especially skilful in working it, and were able to spring off blades of bayonet-like cross-section, half an inch in breadth by six inches or more in length.

While obsidian corresponding to the various kinds of igneous rocks is known, it usually has a composition similar to that of granite, as may be seen from the analysis of a typical specimen from the Yellowstone Park.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	FeS_2	
74.7	13.7	1.0	0.6	0.1	0.8	3.9	4.0	0.6	0.4	=99.8

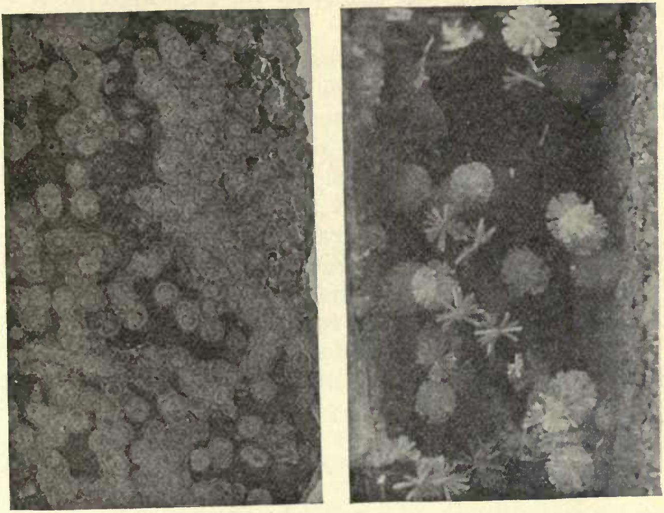
It can be readily shown by calculation that had this magma crystallized, it would have produced a rock consisting of 35 per cent of quartz, 60 per cent of feldspar, with 5 per cent of other minerals, that is to say, a granite. The specific gravity varies from 2.3–2.7, depending on the composition; of the most common variety, 2.3–2.4. The hardness is greater than that of ordinary window glass, which it scratches. Before the blowpipe a splinter of black obsidian fuses readily, with bubbling, to a vesicular gray or white enamel, which, after the removal of the water, becomes exceedingly infusible. This experiment is very instructive in showing the effect of water in lowering the fusing point of magmas and in increasing their liquidity. The water in the obsidian is not the product of alteration, for it is present in what the microscope reveals as the purest and clearest glass, nor are there cavities to contain it; it appears to be chemically a part of the mixture, like Na_2O and K_2O.

Spherulites. In many obsidians may be seen rounded, sometimes perfectly spherical, bodies of white, gray or red color, varying in size from those of microscopic dimensions up to those of an egg, or even larger; usually from the size of fine shot to peas. If closely examined with a lens, it can generally be seen that they are composed of fibers radiating from a common center; at uniform distances from the center the fibers are apt to change color, or to be saturated with a differently colored material, and the body appears built of successive concentric shells. These bodies are called *spherulites* and are composed of fibers of feldspar. They are indicative of sudden cooling and a very rapidly induced crystallization, the fibers shooting outward from some center where crystallization commences, and branching as they grow, until checked by the viscosity of the rapidly cooling magma. They should not be confused with phenocrysts which are single, individual crystals. An example is shown on Plate 21. They are sometimes formed by accident in artificial glass, as seen on Plate 21; in this case the artificial mineral forming them is wollastonite, $CaSiO_3$.

Frequently the spherulites form before the lava has come to rest and are thus drawn out, so that they are dotted along the rock in lines. When in great numbers, and minute, they may coalesce; some streaks of the rock are then composed of them, while other bands are of dark, solid glass, as shown in Plate 22.

Lithophysae. Closely connected with the spherulites there occur also in glassy rocks peculiar formations known as lithophysae (stone bubbles). These consist of a series of concentric shells of crystalline material, resembling somewhat nested watchglasses, which surround a central cavity, and are more or less separated from each other. They consist of adherent crystals, and are very fragile. When exposed by the breaking of the rock they appear much like flowers with concentric layers of petals. They vary in size from very small to several inches in diameter. The

PLATE 21.



A. Spherulites in Obsidian.

B. Spherulites in Glass.

C. Lithophysae.

D. Lithophysae.

STRUCTURES IN GLASSY ROCKS.

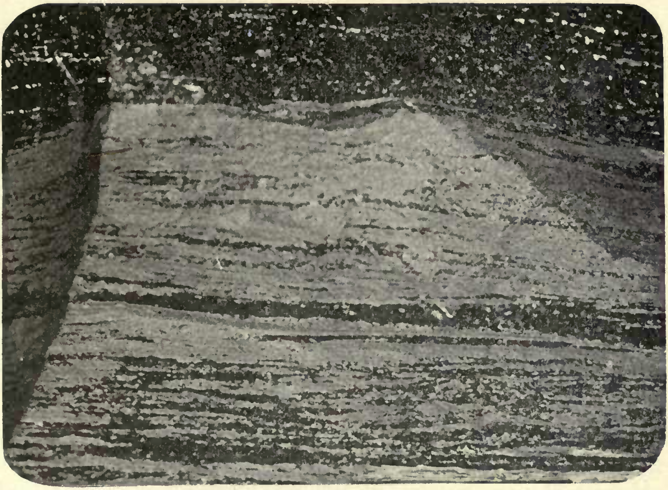
walls of the cavities are coated with minute but beautiful crystals of quartz, tridymite and feldspar, and sometimes fayalite, topaz, garnet and tourmaline are found in them. Sometimes they are more or less flattened and strung along the flowage planes of the rock. They occur, not only in the pure glassy lavas, but also in those which by more or less crystallization have assumed megascopically a stony texture and appearance. They are illustrated on Plate 21. Their origin is ascribed to repeated shells of crystallization, with consequent liberation of water vapor, and expansions of the cavities through its influence under high temperature. The formation of topaz and other minerals points to the presence of fluorine and other accompanying gases. Thus the lithophysae seem to bear a certain analogy to miarolitic cavities in the intrusive rocks, as described elsewhere.

Pitchstone. This may be regarded as merely a variety of obsidian in which the luster, instead of being bright and glassy, is duller and the rock appears resinous or pitchlike. There is also a chemical difference in that, while the water contained in obsidian is rarely so much as one per cent and may sink to mere traces, pitchstone contains much more, as much as 5 or 6 per cent or even greater. It is this which probably influences the luster. They are also variable in color, — black, gray, red, brown, and green, and are translucent to transparent on thin edges.

Perlite. This is a peculiar variety of glassy rock which is composed of small spheroids, usually varying in size from small shot to peas. It is generally of a gray to blue-gray color, rarely red, has a soft, pearly, or wax-like luster and resembles enamel. The spheroids either lie separated in a sort of cement and are then round, or they may be closely compressed and are then polygonal. They tend to have a concentric, shelly structure and are the result of a contraction phenomenon in the cooling glass, which produces a spherical, spiral cracking, as shown in thin sections. Analyses of perlites prove them to have a rather constant percentage of combined water, between 3 and 4 per cent, and there may be a connection between this amount of water and the peculiar method of cracking. To the casual observer they somewhat resemble oölites and pisolites of the concretionary sedimentary rocks. Perlite is produced only by felsitic magmas, especially by those high in silica; it does not occur in basaltic glasses.

Pumice, Scoria, etc. Pumice is highly vesicular glass produced by the extravasation of the water vapor at high temperature, through relief of pressure, as the magma comes to the surface. It is best described as glass froth. Its color is white, gray, yellowish, or brownish, rarely red. It sometimes has a somewhat silky luster. Examined with the lens it is seen to be composed of a mass of silky glass fibers of a cottony appearance, full of pores, and separated by larger holes like a sponge. If drawn out by flowage the fibers are parallel, otherwise they are interwound. The chemical composition of typical pumice is like that of the highly siliceous obsidian, or in other words like that of granite. Pumice does not form independent rock-masses, it occurs as the upper crust of flows of felsite lava, or in fragments among the explosive material ejected by volcanoes. On account of its light, porous nature, and its content of sealed glass cells, it floats almost indefinitely on water, and the material ejected by volcanoes near or in the sea is borne by currents all over the world, and drifts ashore everywhere. Its use as an abrasive and polishing agent, and for toilet purposes, is due to the sharp cutting edges of the thin films and fibers of glass; nearly all that is used comes from the Lipari Islands off the coast of Sicily. Other places of occurrence are mentioned later.

Scoria. While all magmas, whatever their chemical composition, at times and under proper conditions, form pumiceous rocks, typical pumice, as stated above, is most characteristic of the felsitic ones, while basaltic pumices are of local development and of inconsiderable impor-



A. FLOW STRUCTURE IN GLASSY LAVA.

B. SLAGGY STRUCTURE OF BASALTIC LAVA

tance. Nevertheless the basaltic magmas develop through the expansion of gases vesicular forms, as described under basalt. These pass, especially on the upper surface of basalt flows, and in the material thrown out by volcanoes, into more or less glassy, partly stony, dark or reddish, loosely compacted, spongy, cindery or slag-like modifications known as volcanic scoria. This form is illustrated on Plate 23.

A peculiar modification of what may be considered basaltic pumice occurs in the crater of Kilauea in Hawaii, where drops of lava flying up from the boiling lava lakes pull out thin, hair-like threads of glass after them. These threads, drifted by the wind, collect in tow-like masses, called by the natives "Pele's hair" after the titulary goddess of the islands.

Vitrophyre. Either pitchstone or obsidian may contain embedded crystals or phenocrysts which can be recognized. As in felsite porphyries the amount may vary widely from cases where they are rare and widely scattered to those in which the rock is thickly strewn with them. Such porphyries, consisting of a glass base and phenocrysts, are called vitrophyre. Perlite porphyries are known, but are rare. The glassy base of vitrophyre has the properties of the obsidian or pitchstone previously described; it often contains spherulites in addition to the phenocrysts. Of the latter feldspar is the most common; it is very apt to be limpid with a glassy habit; the cleavage distinguishes it from quartz, which may also occur, sometimes alone and sometimes with the feldspar. If phenocrysts of a ferromagnesian mineral are present it is usually biotite, less commonly hornblende, while pyroxene, though known, is rare. The varieties are usually named according to the prevailing phenocryst without regard to the character of the groundmass; so we have *quartz-vitrophyre, feldspar-vitrophyre, quartz-biotite-vitrophyre,* etc. The phenocrysts are generally rather small.

The chemical composition of the vitrophyres is similar on the one hand to the felsites and on the other to the pure glasses; they represent an intermediate stage of development, as may be seen from the following table, which shows the relations of all these varieties of extrusive rocks or lavas to one another.

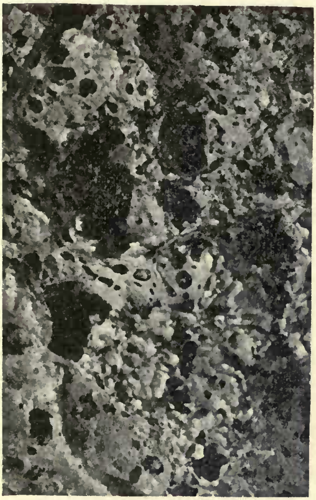
Conditions under which Magma Cooled and Solidified.	No Formation of Crystals in the Depths Before Extrusion, no Phenocrysts.	Crystals Formed in Depth Before Extrusion and Brought up by Magma; Phenocrysts.
No crystallization of magma on surface, on account of rapid cooling. — Glassy texture.	Pitchstone and Obsidian	Vitrophyre.
Crystallization of magma on surface; slower cooling. — Stony texture.	Felsite	Felsite-porphyry.

Tachylite. As previously stated, basaltic magmas crystallize easily and rarely form glass, or only in relatively small volume. Basaltic glass is, however, seen occasionally as a thin marginal facies or selvage in dikes, on lava flows, or among the products of basalt-yielding volcanoes, like those in Hawaii. It is known by the name of *tachylite.*

Occurrence of Glassy Rocks. The glasses are found in those regions which are, or have been in the past, scenes of volcanic activity. While obsidian and pitchstone occur as independent flows and masses near volcanic vents, the glassy rocks in general form only the upper surface of lava sheets, which become crystalline as they are penetrated downward; they are also found, especially in pumiceous forms, in the fragmental material ejected by volcanoes. To attempt to name all the different occurrences would be impracticable, but it may be mentioned that obsidian in large masses is found in the Yellowstone Park and is known for its beautiful spherulites and lithophysae; at Mono Lake in California; Glass Butte, Oregon; White

PLATE 23.

A. VOLCANIC BOMB.



B. SCORIA.

UNIV. OF
CALIFORNIA

C. PUMICE.

Mountains, Utah; Tewan Mountains, New Mexico, and various other places in the United States; in Mexico, Iceland, Lipari Islands, Italy, Hungary, New Zealand, Transcaucasia, etc. Pitchstone occurs in Colorado near Georgetown and at Silver Cliff; well known localities are on the Island of Arran off the west coast of Scotland, in Ireland, and at Meissen and Tharandt near Dresden, Germany. Perlites and pumice are also found in the Yellowstone Park; in Hungary, Italy, Iceland, Japan, etc. Basaltic glasses occur on the west coast of Scotland, in Iceland and especially in the Hawaiian Islands.

Alteration of Glassy Rocks. It has been found by microscopic and field study that ancient lavas, in a variety of places, were once glassy, though not so at present. It appears that when the natural glasses are exposed to the various agencies which tend to alter rocks, such as pressure, heat, action of water, etc., they undergo a slow change, the glass is converted into an intimate mixture of excessively fine particles of quartz and feldspar, and loses entirely its vitreous character. It then assumes the stony texture and becomes a dense felsite. This change is called *devitrification.* While the former glassy condition of many felsites cannot be proved, even microscopically, it may often be suspected in them, from the presence of chains of spherulites, flow structures and lithophysae, which may be seen megascopically, and give strong hints of their former character. Ancient altered lavas of this kind have been described from the coast of Maine; from South Mountain, Pennsylvania; from Wisconsin; from Sweden and other places. In Sweden they have been called *hälleflinta,* though this name is also used to designate somewhat similar rocks of a different origin.

Fragmental Volcanic Rocks.

Origin. The fragmental igneous rocks represent the material thrown out by volcanoes during periods of activity. The explosive action is due to vapors, chiefly that of water, which is contained under pressure in the magma, and as the latter rises to the surface and the pressure is relieved, departs with violence. While the major part is passing off in great volumes, which rush upward and carry the solid or liquid materials to great heights, a minor part is also expanding in the liquid, converting it into cellular vesicular forms. Consequently the solid particles as they fall are commonly found to be of spongy consistency, but mixed with them are often seen compact pieces of lava and other rocks, parts of the solid lava crust formed by cooling after a previous eruption, mingled with fragments torn from the rock walls of the conduit. As the lava continues rising, the greater volume of the gases may pass off, the explosive activity ceases, and the projection of material may be succeeded by quiet outflows of liquid rock. Hence it is very common to find the beds of fragmental material interspersed with layers of compact lava, felsite or basalt.

In this connection it should be also mentioned that the chemical composition of the magma plays a considerable part in explosive activity. Those magmas which correspond to felsite, and are high in silica are, as has been mentioned, very viscous at temperatures where those low in silica, such as the basalt magmas, which are rich in iron, magnesia and lime, are still relatively very liquid. From the former the vapors, on account of their thick viscous condition, escape with difficulty, and with explosive violence; from the latter they pass off readily and easily without explosive activity. While there are many exceptions to this, it may be accepted as a general rule, and we therefore find that vents yielding felsite lavas generally build high and steep cones, composed chiefly of fragmental materials, while basaltic ones are built up largely of liquid outflows and are therefore low and broad. Many volcanoes, like Vesuvius, are of intermediate character in which explosion and projection of material is succeeded by flows of lava, and the cone is consequently of composite character.

Classification. The particles of magma driven into the atmosphere and solidified and the pieces of rock are of all dimensions from the finest dust, which may float for years, to huge masses weighing several hundred pounds. By general usage, for the sake of convenience, the following sizes are roughly distinguished: pieces the size of an apple or larger are called *bombs;* those the size of a nut are termed *lapilli;* those the size of small peas or shot, *ashes;* the finest is known as *volcanic dust.* Sometimes the bombs, lapilli, etc., are sharply angular and sometimes smoothly rounded off — a form caused by the grinding and attrition of the pieces upon one another in the upward rush from the volcanic throat. They should be distinguished from bombs which have been afterwards rounded by the action of running water. The larger bombs sometimes present a sub-angular appearance, are porous and their surface is penetrated by cracks as shown in Plate 23. Such have been called bread-crust bombs. The ashes, and lapilli which usually make up the greater part of the material are frequently spoken of as *volcanic cinders* and cones composed of them are called cinder cones.

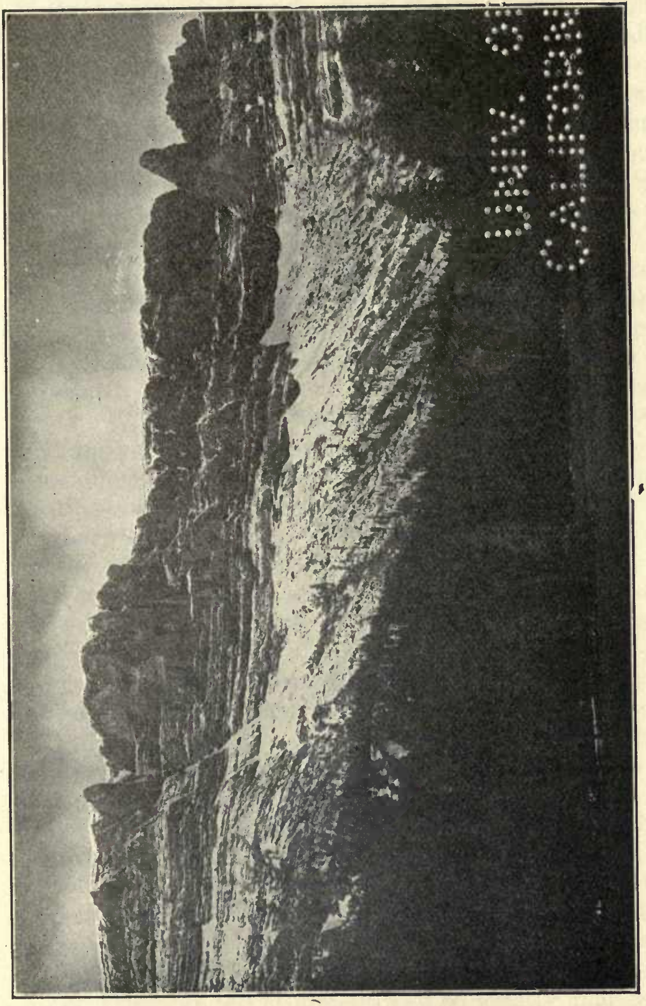
In a sense, of course, this loose material may be estimated as a rock formation; so far as the individual pieces are concerned they are to be considered merely as fragments of the various kinds of rocks treated in the foregoing pages, to be named and described as there set forth.

But in process of time great accumulations of such material may be spread over wide tracts of country, covering up existing rock formations. The heavier and coarser particles fall first, then the finer, giving a gradation from top to bottom and, as successive outbursts occur, there is produced in this way a rough bedding. By its own weight as it accumulates, aided by the action of percolating water which may carry and deposit substances in solution, it gradually becomes compacted into a more or less firm mass, having a certain individuality as a kind of rock and deserving of special treatment. When the rock is composed entirely of the finer particles, dust and ash, it is called *volcanic tuff;* when this is mixed with the coarser bombs and lapilli it is termed volcanic conglomerate, or better, *volcanic breccia,* with reference to the broken angular character of the embedded fragments.

Volcanic Tuff. This is generally a fine-grained rock, light in weight, and often of a chalky consistency, sometimes dense, compact, and breaking into small chips. The color is usually light, white, pink, pale-brown, gray or yellow, sometimes passing into darker shades. The more compact varieties may be easily mistaken for felsite lavas; it is possible, indeed, in some cases, that they cannot be distinguished from them megascopically, but generally attentive examination with a good lens will reveal angular particles of quartz, feldspar, and often other minerals in them, and possibly small fragments of other rocks. When breathed upon, they usually exhale a strong argillaceous odor, probably owing to partial or complete alteration of feldspathic particles to clay. When not too compact they have a rough feel and yield a gritty dust, when strongly rubbed between the fingers, unlike the smoothness of pure clay or chalk, owing to the hard, angular character of the dust particles. Sometimes such tuffs contain fossil remains of vegetation, when they have fallen upon land surfaces covered with it, and carbonaceous remains of stems, twigs, or leaf imprints may be found in them. If the material has fallen into water the tuff may be rich in various kinds of fossils, such as marine organisms, of possibly great perfection of form, and for the same reason it may be well stratified. All of these varied characters, including the mode of occurrence and relation to other rocks, must be taken into account in judging the nature of the deposit.

Volcanic Breccia. This has a base or cement of tuff, more or less completely filled with lapilli of angular shapes, and these are often mingled with larger bombs and masses which are apt to be rounded. Interspersed

PLATE 24.



UNIV. CALIF.

BEDDED VOLCANIC BRECCIAS, TABLE MOUNTAIN, ABSAROKA RANGE, WYOMING.

(U. S. Geological Survey.)

with these are apt to be fragments of other rocks, pieces of the basement through which the conduit has drilled, of limestones, shales, sandstones, and massive crystalline rocks, granite, gneiss, schist, etc. They have therefore a strongly conglomeratic aspect, like the specimens seen in Plate 32. Even when these rocks have been greatly indurated by contact metamorphism, or other agencies, they still reveal, by differences of color and texture on a freshly broken face, the angular shapes of the fragments and their composite character. When not too indurated they are apt to erode very unevenly; the finer cement being less resistant washes away first, leaving the contained masses projecting, and in this way along the edges of cliffs strange and weirdly shaped figures of erosion are produced, called "hoodoos" in the Rocky Mountains' region. The colors of these breccias is variable, browns, reds and chocolate being common, along with lighter tones, depending partly on the state of oxidation of the iron-bearing compounds they contain, and partly on the nature of the magma, whether felsitic, which tends to lighter colors, or basaltic which produces darker ones.

Occurrence of Tuffs and Breccias. These rocks are of wide distribution, being found in all regions where volcanic activity has taken place; their presence indeed is the best confirmation in many regions of such activity in the past. In places where vulcanism is still active, or has only recently ceased, they are represented by the still uncompacted material, but no definite line can be drawn between the different conditions of consolidation.

In the eastern United States, tuffs and breccias have been found in several localities in Maine; near Boston; and at South Mountain, Penn. They occur also, to a limited extent, with the Triassic eruptives of the Connecticut Valley. Further research will probably reveal other localities, but they are neither common nor conspicuous rocks, being limited in volume and so greatly changed in character by various agencies that in many places their true character is difficultly recognizable. They probably had once a much greater extension, but erosion has mostly carried them away, during the vast period of time which has elapsed since volcanic activity was displayed.

In western America, however, the case is very different; in the various ranges of the Rocky Mountains; in the Coast and Cascade Ranges, and in fact over most of western North America, these are common rocks and in many places in Colorado, Wyoming and Montana, they occur in immense deposits, forming often an important factor in building up the bulk of the mountain masses. They are especially well displayed in western Wyoming, in the region of the Yellowstone Park, where the serried peaks of the Absaroka Range are mostly carved out of tuffs and breccias aggregating thousands of feet in depth, thus testifying to the enormous volcanic energies which this region formerly displayed. A section cut into them by erosion, exhibiting their rough bedding, is shown in Plate 24. In this region they are frequently interbedded with flows of lava.

In Europe tuffs and breccias have a wide extension. They occur in many places in the British Islands, as in the Lake district in northern England, and associated with the volcanic rocks of the old red sandstone and Carboniferous of Scotland. They are often interbedded with sedimentary rocks and are frequently so changed by metamorphic processes as to be recognized only by careful petrographic research, having been changed into slates, etc. Such altered tuffs form a part of the so-called "hälleflintas" in Sweden or the "porphyroids" of Continental geologists. Tuffs and breccias occur in many places in Germany, France, Italy, etc. The mention of these localities is sufficient to show their wide extension and importance. In this connection the reader is referred to what is said of adobe.

CHAPTER VIII.

ORIGIN AND CLASSIFICATION OF STRATIFIED ROCKS.

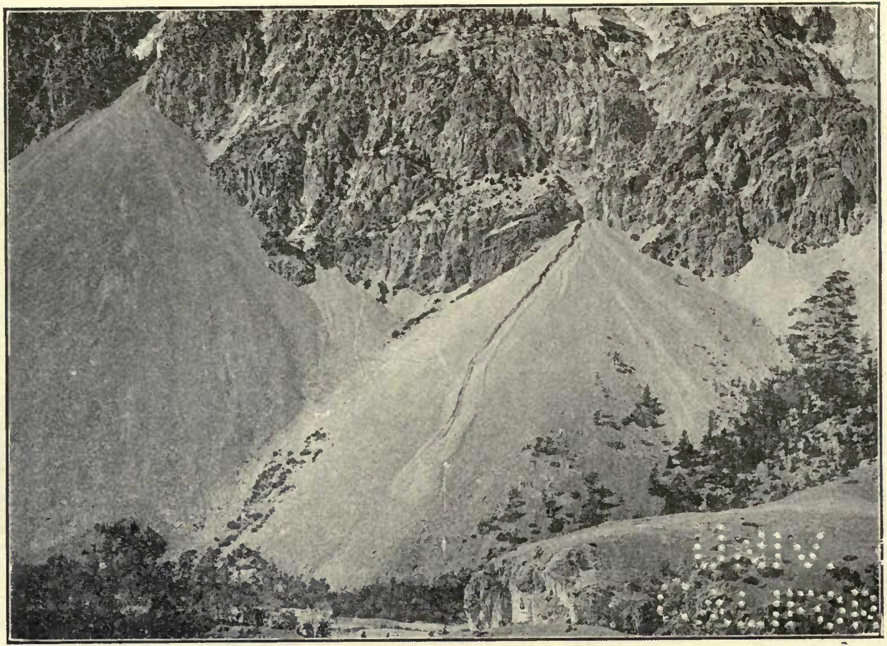
The stratified rocks consist of material which has already formed a part of pre-existent ones, and which has been deposited from some fluid by which it has been moved from its former position. The shifted material may have been moved and deposited by the action of water, the atmosphere, or glacial ice. The first case is by far the most prominent and important, especially with respect to the volume of the masses involved, and the frequency of their occurrence, and thus when stratified rocks are mentioned such water-formed rocks are always understood, unless it is otherwise stated. In contradistinction to them, the material which has been moved and deposited by the action of the atmosphere, forms the class known as *Aeolian rocks,* one of far less importance. From what has been said, it is clear that the stratified rocks are *secondary* ones in the respect that their material in some form or other has been derived from already existent ones. An exception to this would be found in beds of coal, which are truly stratified rocks derived from plant life, or in beds of volcanic ashes which have been deposited from the atmosphere, and which have been described by preference under the igneous rocks. But in general the statement, that the material of the stratified rocks is secondary, holds true, and it has been derived from former rocks of all classes — igneous, metamorphic and stratified — and in the case of the earliest sediments from the earth's original crust, if such ever existed.

The rocks which have been formed in water may be divided into two main groups, according to the manner in which the material has been deposited; they consist either of substances mechanically held in suspension, and then directly dropped, or of that which has been in solution, and through chemical agencies, either of organic life or otherwise, has been rendered insoluble, and has been therefore deposited. The first we may call *mechanical*, the second *chemical* sediments. Yet even between these, as we shall see later, it is difficult to draw a definite line. We have then the following classes to deal with:

Sedimentary rocks; water-formed	mechanical. chemical.
Aeolian rocks; wind formed . .	mechanical.

Decay of Rocks; Formation of Soil. When firm and even dense rocks are exposed to the action of the atmosphere, they gradually decay and are turned into soil. This is brought about by a variety of agencies. All rock masses are penetrated in various directions by cracks and fissures called *joints;* these are both great and small, and in addition the individual mineral grains contain cleavage and other cracks. Thus water is able to thoroughly permeate the rock masses, and in cold regions where alternate thawing and freezing goes on, the expansion of the water in turning to ice keeps on splitting and crumbling the rocks until on the surface they are reduced to a mass of débris. The expansion and contraction of rocks in hot countries and in arid regions, under great daily and yearly changes of temperature, accomplishes the same thing more slowly. The expansion of the growing roots of trees and plants tends to the same end. By such processes there is a constant tendency for the rock masses to be broken up, *mechanically,* into smaller and smaller fragments. In the meantime the substances dissolved in the water, such as air, acids from decaying vegetation, and especially carbonic acid gas, are acting *chemically* upon the rock minerals, converting the silicates, oxides, and sulphides into other forms, into carbonates, hydrated silicates, hydroxides,

PLATE 25.



TALUS CONES, SHOWING MOVEMENT OF ROCK WASTE, HEAD OF STINKING WATER RIVER, WYOMING.

(U. S. Geological Survey.)

sulphates, etc. Much material goes into solution, is leached out, and by running water is carried into lakes and the ocean, where it concentrates, and where we must again consider it under the formation of the chemically precipitated sediments. Some minerals, such as quartz, are not attacked to any appreciable extent, or but very slowly, under ordinary circumstances, and these remain to form the chief part of the rock débris. It is for this reason that silicates, and especially quartz, play the chief mineral rôle in the sedimentary rocks formed by mechanical processes. This débris of broken, crumbled and altered rock, which constitutes a detritus, has been called by various names, and the finer upper portion in which vegetation grows is the soil. Under this latter name for convenience we may consider all of it. The gradual change from rock below to soil above is illustrated in Plate 17.

Movement of Soil. The surface of the land in general is covered by a mantle of soil resting on the rocky crust of the earth. The latter, which is popularly known as the "country rock," here and there in ledges, precipices, and the craggy tops of hills and mountains projects through this covering. By the action of running water, aided by gravity, this crumbled rock and soil mantle, which is apparently at rest, is, geologically considered, actually in motion, and is continually being urged downward into the sea, its ultimate goal, Plate 25. On steep slopes it goes more rapidly, in valleys more slowly; in level plains, like water in a lake, it is temporarily impounded. Its rate of motion varies continually from time to time and from place to place. Its movement in mass is of course very slow; when suspended in running water, that of the water which carries it; when resting on the stream bottom it varies according to circumstances. Thus the land waste is being ever carried away and ever renewed by the destruction of the rocks. The greater part is carried into the sea, but a considerable part is deposited in inland lakes and seas, and on the lower plains and deltas of great rivers, which from time to time are heavily flooded. It is this material which forms the sedimentary rocks of mechanical deposition.

Gradation of Material. The detritus of the land consists of material of very variable sizes, and in northern countries over which glaciers have passed this is particularly apt to be the case, as rock masses showing great extremes in dimensions are moved and mingled by them. When such material is moved by running water it becomes sorted and graded, according to the strength of the current, into masses consisting approximately of equal sized particles. When they are larger than peas the material is called *gravel* and the individual pieces are termed *pebbles;* large, loose pieces of rock from the size of a small melon up are spoken of as *boulders.* Pieces smaller than peas, which form a non-cohering mass when wet with water, are termed *sand,* while the finest particles which are readily lifted and transported by movements of the atmosphere are known as *dust,* and these when wet and then dried generally cohere into solid material. All these grade into one another. The following table shows a more accurate division according to size.

Name of Material.	Diameter in Millimeters.
Fine Gravel . . .	2–1
Coarse Sand . . .	1–0.5
Medium Sand . .	0.5–0.25
Fine Sand	0.25–0.1
Very fine Sand . .	0.1–0.05
Silt	0.05–0.01
Fine Silt	0.01–0.005
Clay	0.005–0.0001

Thus, roughly speaking, the material may be classified into, (*a*) gravel, (*b*) sand, (*c*) mud, clay or silt. Since this division is made the basis of classification of the mechanically formed sedimentary rocks, each of them may be examined somewhat more in detail.

Gravel. The pebbles which compose a gravel are pieces of individual rocks and like them are generally made up of grains of different kinds of minerals. In some cases they are composed of only one mineral, and of these, quartz is by far the most common. Such quartz pebbles may be fragments derived from quartzite strata, from a quartz vein, or from large quartz crystals from some granite-pegmatite dike. Such coarse granites or pegmatites may furnish pebbles consisting of other single minerals, especially feldspar.

The form and appearance of pebbles depends on the conditions to which they have been exposed. Those which have suffered considerable transport in the bed of streams, or have been rolled on the shores of lakes and of the sea, are, as is well known, rounded and become ovoid to spherical. They are apt to have a very smooth surface with a characteristic faintly dimpled, slightly dented, or inverted shagreen appearance, caused by their repeated collisions under movement. This is best seen on a pebble of a hard homogeneous substance, as in one of quartz. If composite in nature they are often pitted by the decay and removal of softer or more easily altered particles.

The degree of rounding shown by pebbles depends on the distance and length of time they have been transported and on the hardness of the material. Sedimentary rocks, as will be shown, are sometimes composed of pebble-sized fragments, which have suffered very little movement, and which still retain their original rough, angular character.

Pebbles and boulders which have been transported by glaciers are sometimes seen in sedimentary rocks. These have characteristic sub-angular forms, with faces ground upon them, which are polished and scratched by parallel and crossing grooves or scratches. Pebbles, partly buried in the sand of the seashore and of deserts, are also often subangular and facetted, the faces being ground by the sand drifting past them, but these lack the scratches.

Pebbles buried in the soil often show fern or moss-like markings or dendrites upon them, or are sometimes covered with a shiny skin of dark color. This comes from a deposit from water, of manganese or iron oxides.

Sand. Strictly speaking, sand means particles of a certain size, as mentioned above, and has no reference to their composition: thus we have quartz sand, coral sand, volcanic sand, etc. It happens, however, that by far the greater part of the sands are composed of particles of quartz, and some are exclusively made up of it. For this reason when sand is spoken of briefly, quartz sand is always understood.

The composition of ordinary sand is quite variable, depending on the locality. In addition to the quartz grains, those of many other minerals are present, depending on the rocks of the region. Feldspar, garnet and iron ore are very common. Various silicates such as hornblende, pyroxene, tourmaline, etc., are apt to occur. Some grains may be made of pieces of very fine-grained rocks of composite character. Twenty-three different kinds of minerals were found in the dune sands of Holland by Retgers.

Like pebbles the sand grains are more or less rounded, depending on the amount of transport. In some rather coarse sea sands they are almost all spherical. Below a certain degree of fineness the grains do not become more rounded by attrition in water among themselves; this is due to the fact that the capillary film of water covering them acts as a buffer and prevents them from coming in contact when they collide; in the larger grains it is not able to do this.

Mud, Silt and Clay. This consists of the finest material of the land waste. As sedimentary deposits they are characteristically found off shore, or in sheltered bays and sounds, where the slow movement of the water does not permit the transport of the heavier sand and gravel, and as the material forming the lower flood plains and deltas of great rivers. On account of their minute size the particles are little apt to be rounded, but under the microscope show angular forms. Like the sands they may be composed of a great variety of minerals, kaolin, mica, quartz, feldspar, etc., but just as quartz is the characteristic mineral of the sands, so is kaolin that of muds and clays. As shown elsewhere the decay of the feldspars of the rocks produces kaolin or clay, while the quartz grains are unaltered; the clay particles are excessively fine and light, while the quartz ones are mostly larger and heavier. From this there tends to be a separation of the two by moving water; as the current slackens the quartz is deposited first, forming sand, while the lighter clays are carried beyond and settle in still water. Fine flakes of white mica are apt to accompany them.

In fresh water a portion of most clays, consisting of the very finest and lightest particles, will remain in suspension almost indefinitely. Turbid water of this kind acts much as if it were a solution of clay in water; if salts be added to it, or if it be mixed with sea water, the clay then curdles into lumps or flocculates and is quickly deposited, leaving the liquid clear. This behavior is analogous to that of salts in solution, and it has an important bearing on the deposition of material carried into the sea, and on the formation of certain kinds of rocks.

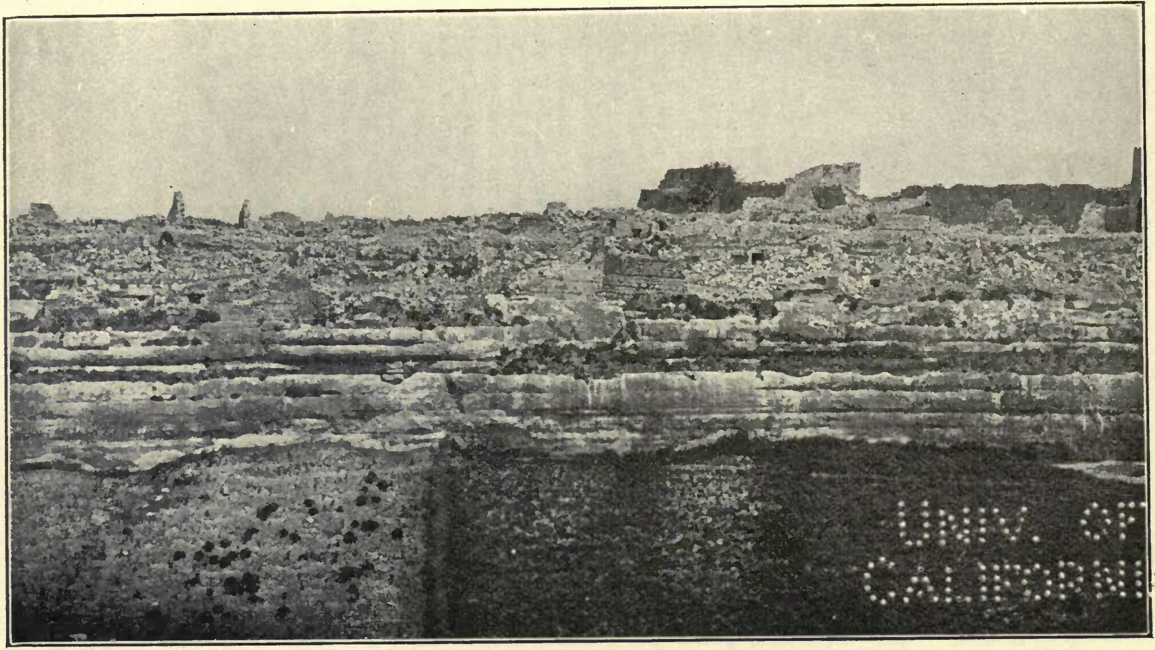
Muds or clays are characterized according to the predominance of certain constituents; thus some are calcareous, containing more or less carbonate of lime and are often called *marls;* some contain a good deal of fine quartz and are spoken of as siliceous, others are rich in deposited iron oxides and are ferrugineous clays or ochers, while in many these constituents are present in minimum amount, or are wanting, and these are plain clays or argillaceous deposits. Such mixed forms are transitional to the chemically deposited rocks described later.

Dissolved Material. The waste of the land includes not only the material mechanically transported by water, but also that which is taken into solution and ultimately carried into the sea. A rough estimate of this for the continents places it at 5,000,000,000 tons per annum. It is an important fraction of the whole amount removed, compared with the mechanical sediments. It varies greatly in different rivers, depending on the composition of the rocks forming their basins. It is inferred that through the concentration of this material in solution during past ages the salts now in the ocean have been produced. From these salts, those sedimentary rocks, whose material through chemical agencies, either of organic life or otherwise, has been redeposited from solution, have been formed. It includes the important class of carbonates, limestones, dolomites, etc., and the less important sulphates and chlorides, such as gypsum and rock-salt.

It is probable that the carbonates of lime, magnesia, and alkalies were all originally derived from silicates of these oxides. Water containing carbon dioxide has converted them into carbonates, as illustrated under the decomposition of feldspar, and has then dissolved and carried them into the sea. The sulphates have been formed by the oxidation of sulphides in the original rocks and the union of the sulphuric acid with the stronger, more soluble, alkaline bases. The chlorides have in part been derived from minerals of the original rocks and, perhaps, made in part by volcanic emissions from deeply seated magmas within the earth.

Structure of the Sedimentary Rocks. The sedimentary rocks, as geological masses, differ greatly from the igneous ones in that they form widely extended, relatively thin bodies, making part of a coating or mantle upon the earth's outer surface; they never prolong themselves by extension into the depths, as the latter always do. It is thus their horizontal, as contrasted with their vertical extension, which gives them importance as geological masses. The most characteristic feature about their structure is that they are *stratified*. This means that they consist of layers, varying in material, texture and color, and in thickness, which, if undisturbed by geological events more recent than their formation, are in general horizontally disposed one upon another. This is illustrated on Plate 26. It is due to the fact that the mechanical sediments have been deposited by moving currents of water in lakes and seas and on the flood plains of rivers, and these currents,

PLATE 26.



STRATIFIED BEDS OF LIMESTONE, CRIMEA, RUSSIA.

acting with diverse material and continually varying in strength, have assorted the sediments and deposited them in strata. For further consideration of this subject information should be sought in any of the numerous manuals of Geology, but it may be stated as a general law that sedimentary deposits are always stratified and that, conversely, perfect stratification, resulting from an assortment of particles, is regarded as a proof of deposit in water.

Volcanic ash deposits are commonly rudely and sometimes well stratified; the heavier of the particles projected upward falling first to be succeeded by smaller lighter ones; repetitions of the process make individualized beds and thus a rude stratification (see Plate 24,) while the lighter dust may be deposited by moving air currents much as if in water.

For stratification variation, both of conditions and in the size of the particles, is necessary; during a period in which uniformity prevails in either it will be wanting. Thus aeolian deposits, which consist of the finest sands and dust driven by the wind, are often so uniform with respect to the size of the particles in any one area that no stratification, or but very little, is produced. In the same way deposits of carbonate of lime, as limestone and chalk, in the open ocean may take place under such uniform conditions and size of particles that beds of these rocks, perhaps a hundred feet in thickness or more, are quite structureless and devoid of apparent stratification throughout that extent.

Mere parallelism of layers in a rock is not in itself a mark of stratification and therefore a proof that the rock exhibiting it is of sedimentary origin. Its mineral composition, texture, and relation to the accompanying rock masses, and to the general geology of the region, must also be taken into consideration. For the spreading action of flowing lava may draw out portions of unlike character within it into thin superimposed sheets as illustrated in Plate 22. Such lavas when fresh are easily recognizable, but buried in the midst of sedimentary deposits and changed in appearance by geologic ages of exposure to various agencies, they may be confused with the accompanying stratified rocks. And again very perfect parallelism of layers and structure may be induced in all kinds of rocks by the shearing and metamorphism accompanying movements of the earth's crust and mountain building. These may superficially simulate stratification quite perfectly, but consideration of the points mentioned above is generally sufficient to show the difference between them. Many serious errors in understanding the real origin of the rocks of different places and their geology have occurred in the past through failure to properly appreciate these facts.

The individual layers of stratified rocks, which are uniform in texture, color and composition, may vary from the thinness of paper to a hundred feet or more. Usually, it will be observed that a certain layer, which has a general similarity of character and composition that serve to distinguish it clearly from others above and below, is made up of much smaller subdivisions whose differences from one another are not very marked. The larger division is usually known as a *layer* or *bed*, the smaller ones are termed *laminæ*. The main differences between laminæ are generally in coloration; as shown in Plate 33, between beds in texture and composition. As explained above, under uniform conditions *laminæ* may be wanting in a particular bed. The general homogeneity of a bed is shown by its particular hardness and appearance, its individual method of cracking or jointing, and the way in which it is affected by erosion, which differs from the beds above and below it. A collection of beds lying concordantly one above another, and deposited during a given geological period of time, is called a *formation*.

Texture of Sedimentary Rocks. This depends upon the relative size of the particles, which determine the fineness or coarseness of grain, upon their shape, and upon the amount and character of the cement, which determines the firmness or friability of the rock. The *size of grain* varies within wide bounds, but as explained previously under gradation of material, this in itself determines largely the kind of rock. Thus conglomerates are of necessity coarse-grained rocks; sandstones, medium-grained ones, and shales, fine-grained or compact. Still within the limits of each class there is variation in this respect and we are accustomed to speak of fine, medium and coarse-grained sandstones; a medium grain in this rock is about that of ordinary loaf sugar.

The *shape* of the component grains, when these are megascopically visible, depends on the amount of transport which they have suffered, as explained under gravel. Usually they are more or less rounded or ovoid, but sometimes quite angular. The latter is more apt to be the case as the size of grain increases. Sometimes this broken, angular character of the particles can be distinctly seen in medium-grained sandstones and arkoses by close observation with a good lens. It shows the rock to have a distinctly *clastic* nature. In the case of coarser rocks and in conglomerates it becomes very striking, and such rocks are called *breccias* and are said to have a brecciated structure. This is illustrated in Plate 32. Such breccias are not to be confused, however, with volcanic breccias, as described on page 272.

The *cement* is that which binds the particles of sedimentary rocks together and converts them from loose material into firm rock. Various substances act in this capacity, according to circumstances; sometimes it is carried into the rock from outside sources in solution and deposited in its pores, sometimes part of the sediment itself goes into solution and is redeposited, and sometimes it consists of fine material mechanically enclosed with the sediment. In the first and second cases silica and carbonate of lime are common binding materials, in the third, clay or clay-like substances perform this function. Iron oxide, probably according to the second case, is also a not uncommon cement in the form of hematite, or göthite, or limonite. The fine deposits of mud and clay appear to be able to consolidate into firm rocks, under the pressure of superincumbent masses, without the presence of a perceptible cement, though it is sometimes present.

The firmness of the rock depends then, in part on the amount of cement and its quality, and in part on the pressure. As a result all degrees of this character are shown by sedimentary rocks; some are very hard, firm and compact, breaking like igneous rocks under the hammer and susceptible of a polish, as in the case of some limestones and sandstones, while others are so loose, incoherent and friable that they may be readily rubbed to powder under the fingers, as with chalks and some sandstones. And all gradations may be found between these extremes.

Color of Sedimentary Rocks. This depends partly on the color of the constituent mineral grains or particles, and partly on included substances which act as a pigment. The most common minerals which form the sedimentary rocks are quartz, kaolin, feldspar, calcite and dolomite; these are white or colorless substances naturally, though they sometimes display exotic coloration, and rocks composed purely of them, without included pigment, are white, as illustrated by certain sandstones, clays and chalk. Generally more or less pigment is present, and the common ones are the oxides of iron and carbonaceous matter. The iron occurs in the form of ferric oxides, or hydrated oxides, as hematite, or probably hydrohematite (turgite), which gives red to red-brown colors, or as limonite, or göthite, which produce yellow to yellowish brown tones. Carbonaceous matter or finely divided carbon is black, and this is the color of the rock, if it contains an excess of it; as the amount lessens dark grays are formed, and so on into pale grays. If both organic carbonaceous matter and iron oxides are present in the rock, the former exerts a controlling power over the coloring capacity of the latter in this way; in the presence of organic matter, especially when it is decaying, iron is reduced from the ferric to the ferrous condition, it changes from ferric oxide to ferrous carbonate, and as ferrous compounds are colorless or light-colored the rock has the tones of color produced by the carbonaceous pigment. If such rocks are exposed to weathering and the carbonaceous material destroyed, the iron is reoxidized and the red and yellow colors show themselves. This is illustrated in the outcrops and on the joint faces of many black slates which weather red or yellow. On the other hand if the rocks are devoid of iron, when the organic pigment bleaches out, they become white or very light in color. And again, if solutions containing organic matter leach through the rocks, the iron oxide is not only changed into the ferrous condition, but when reduced to this state, or in it originally, goes into solution also and is carried out, the rocks thus becoming light or colorless.

The most common colors then for the sedimentary rocks are white to light gray, to dark gray and black, or from white to pink into red, to dark red and red-brown, or from pale yellow to buff, to yellow-brown. The reds and yellows are often seen commingled in the same rock mass or layer, according to the varying iron hydroxides. In the case of conglomerates and coarse arkose sandstones, these colors may be modified by those of the fragments of the unchanged original rocks which they may contain.

Chemically formed Rocks. These rocks are formed in those cases where material, which has been in solution, has become insoluble by reason of some agency, and is precipitated. The chief agencies involved are concentration of the solutions and organic life. In the latter case animals living in water, chiefly in the sea, secrete inorganic material in the production of their hard parts, either skeletons to stiffen them, or shells as defensive armor for their soft organisms. As the animals die these collect as deposits. The chief substances secreted are carbonate of lime, $CaCO_3$, and silica, SiO_2, the former being much the more abundant and important. Examples are seen in the formation of reefs and islands by corals, and in the shell-banks made by mollusks. Vegetable organisms also, under certain conditions, secrete silica, and give rise to deposits of that substance.

The deposits produced by concentration occur when bodies of sea-water are isolated from the ocean by geologic processes and become so concentrated by evaporation that they are no longer able to retain the salts in solution. These are then deposited in the order of their solubility. Gypsum and anhydrite, sulphates of lime, and common salt, sodium chloride, are the most important substances deposited in this way. The same result occurs in lakes and inland seas in arid regions, which have no outlet and where there is a steady concentration of material in solution, brought into them by inflowing streams. Carbonates, sulphates and chlorides are the main salts deposited. In a somewhat similar manner, when water passing through the rocks becomes mineralized by taking substances into solution and then attains the outer air, as in springs, these substances are deposited. Such deposits are, with respect to the masses involved, geologically speaking, of minor importance, and are illustrated by the deposits of carbonate of lime around springs, and in caves, and of silica around geysers and hot-springs in volcanic regions. A more important case is where water, in the presence of organic matter, has leached iron oxide from the rocks and soils and carrying it in solution into swamps and shallow waters, has there deposited it, either in the form of ferrous carbonate (siderite), if there is excess of organic matter present, or in the reoxidized form of ferric hydroxide (limonite) if it is wanting. By this means widely extended beds of iron ore have been formed, which are of great technical value and importance.

Circulation of Material. Geological science is not yet in a position to state definitely concerning the origin of the material of the earliest formed sediments upon the earth. We have only the fact that, wherever upon the continents the deepest amounts of erosion have occurred and the basement upon which the visibly earliest sediments have been deposited is exposed, this basement is of igneous rock or of apparently igneous rock which has been metamorphosed, and the sediments such as could have been derived from its erosion and weathering. Whatever the nature of the original sediments was, it is evident that when they had been elevated to form land, since erosive processes continued, any new sediments would be derived from the old ones plus any material that would be added by the continued erosion of such areas of the original surface as the first sediments had not covered and which still remained land, and of any fresh igneous rocks which had come up to occupy a place in either. This condition of affairs has continued to the present time; sediments have been laid down, and then elevated to form land, sometimes being greatly metamorphosed in the process and sometimes not, and these by their erosion have in turn yielded fresh sediments, and so on. Thus there has been a circulatory round of material, with changes of conditions to affect the minerals at each stage, and only the most resistant, such as quartz, have been able to undergo it without change. One is a downward course from land to sea; the return journey is the ascension of the land from the sea. The silicate minerals, which chiefly form the mechanical sediments, have performed the downward journey in suspension, the carbonate minerals, on the other hand, have made it mainly in solution. This means that sandstone, for example, on erosion is mostly carried away mechanically, while limestone, which consists mainly or entirely of carbonate of lime, ultimately disappears mostly by going into solution, although at the beginning of erosive work upon it, it may be largely mechanical processes, which break down the rock. Some cases of mechanical sediments consisting of carbonate of lime occur, though not relatively of great importance, and these are described under limestone, along with some deposits of lime formed on land by evaporation, which may be regarded as temporary stoppages of the material in solution on its way to the sea. This latter case is illustrated in the formation of travertine around springs and in caves.

Minerals of the Sedimentary Rocks. From what has been said in the foregoing pages, it is evident that the minerals of the sedimentary rocks consist of those which compose the igneous ones and which have been able to endure without change the various conditions to which they have been subjected, as well as the new ones formed by weathering and erosion. The finer the material and the longer the time of its transport has been, the more thoroughly it will be changed into new mineral combinations. Hence quartz and feldspar are important in the coarser-grained rocks, quartz, kaolin and mica in the finer-grained ones; while calcite, dolomite, siderite, limonite and gypsum represent minerals of the chemical deposits. In the fine-grained and dense sedimentary rocks, formed of silts, muds and clays, the particles are so fine, that from the megascopic point of view the mineralogical composition is an element of little value in determining and classifying the rock, compared with its color, texture, structure, hardness and other qualities.

Chemical Relationships. The chemical and mineralogical composition of sedimentary rocks is not dependent on definite laws, as that of the igneous rocks evidently is. There are no rules governing the associations of minerals, since these have been brought together by chance, depending mostly on specific gravity, and on size of grain in the assortment. The chemical composition has not in consequence the same significance that it has in igneous rocks. Analyses of a few of the more important types are given in the following descriptive portion, since these may be useful in several ways.

Classification of Sedimentary Rocks. Two modes are used to classify the stratified rocks; one, without reference to composition and character, is based upon the period of their formation in the geological time scale; the other is founded on composition and physical characters. According to the first, strata are classified as Cambrian, Devonian, Jurassic, Tertiary, etc.; according to the second, as sandstones, limestones, etc. The first has its bearing in historical geology, the second is the petrological method, and is the one that concerns us here. In this work the following classification is adopted.

Classification of Stratified Rocks.

1. Material of chemical origin, from solutions.
    - *a.* Deposits from concentration.
        - Sulphates; GYPSUM and ANHYDRITE.
        - Chlorides; ROCK-SALT.
        - Silica; GEYSERITE and related rocks.
        - Carbonates; TRAVERTINE and related rocks.
        - IRON ORES of several kinds.
    - *b.* Deposits through organic life.*
        - Carbonates; LIMESTONE and DOLOMITE.
        - Silica; FLINT and related rocks.
        - *Phosphate rock.*
        - COAL, *asphalt,* etc.
2. Material of Mechanical Origin.
    - *a.* Water-laid deposits.
        - CONGLOMERATES and BRECCIAS.
        - SANDSTONES.
        - SHALES.
    - *b.* Wind-formed deposits.
        - *Loess.*
        - *Dune-sands.*
        - *Volcanic ashes.*
    - *c.* Surface accumulations.
        - *Laterite* and various soils.

In the nature of things a classification of stratified rocks cannot always draw exact lines between different kinds of rocks. For shales may pass into limestones on the one

---

* Geyserite, Travertine, and Iron Ore may be also partly organic.

hand, and into sandstones on the other, and no sharply-defined boundary can be drawn between them. Many such instances could be cited.* And in cases of many rocks of mixed materials and origin it would be difficult to know just where to assign them. The classification must be considered as based upon clear and unmistakable types, which serve as center points around which the rocks group themselves. In the descriptive portion which follows, the exact order of this classification, in respect to some minor rocks, for convenience in reference, may not be always exactly followed.

---

* Thus geyserite and travertine are in places and at times partly organic in origin.

CHAPTER IX.

DESCRIPTION OF STRATIFIED ROCKS.

Chemical Deposits by Concentration and Organic Agencies.

The more important of the deposits produced from aqueous solutions by the material becoming insoluble through concentration are gypsum, anhydrite, rock-salt and calcium carbonate. Certain deposits of silica from hot waters should also be placed here and iron ores as well, although in the latter case the process of deposition is not usually one of simple concentration. The connection between gypsum, anhydrite and rock-salt, in respect to their origin and occurrence, is very close. They are formed in bodies of sea-water that have been separated from the ocean by the raising of coast-lines, or by accumulations of deposits, and under such climatic conditions that the isolated water concentrates by evaporation to such a degree that its salts must crystallize out of solution and deposit. Or in a similar way they may be formed in inland lakes, which have no outlet because they are in arid regions, where the evaporation equals or exceeds the amount of inflow. All natural flowing waters contain more or less of various salts in solution, and in such a lake they must indefinitely increase until the depositing point of concentration is reached.

GYPSUM.

As a rock, gypsum is fine-grained to compact; sometimes a foliated aggregate showing the excellent cleavage of the mineral; sometimes it has a fine fibrous structure; these forms are less common than the first one. The foliated is sometimes cavernous with crystal ends projecting into the cavities, and this may be from recrystallization of the more compact varieties. The fibrous variety is more apt to occur when gypsum forms thin layers or lenses in shales and sandstones. The usual color is white, but it is sometimes yellow or red from iron oxides, or gray to dark gray from mingled clay or organic matter. It is soft and easily scratched with the finger nail. For other properties reference may be had to the description of gypsum as a mineral.

Gypsum is likely to be accompanied by a great variety of minerals depending on the local occurrence. The most common and intimately related of these are rock-salt and anhydrite, the three having a common origin as previously stated. Clay, marl and bitumen are common impurities. Dolomite, calcite, quartz, sulphur, iron pyrites, are not uncommon accessory constituents. Varieties containing bituminous substances generally yield a disagreeable odor when broken. Gypsum is used in the manufacture of plaster of Paris, and in the raw state as fertilizer. The very compact white or tinted varieties are sometimes called *alabaster*, and cut into ornamental forms, vases, etc.

Occurrence. Gypsum is widely distributed in the stratified rocks, in the form of extensive beds, often of great thickness, and is especially associated with limestones and shales. It is very commonly found accompanying beds of rock-salt; in such cases it is likely to underlie the salt. It is also found in sedimentary formations, especially in clays and shales, in lenticular masses or scattered through them in isolated crystals, sometimes of great size, as in the Cretaceous beds of the western United States.

It also occurs in volcanic regions, around fumaroles, where sulphurous vapors are escaping, and especially where limestones have been subjected to such action. In some places where it is found in rocks it may be due to the oxidation of iron pyrites and a chemical reaction of the product with carbonate of lime.

ANHYDRITE.

As a rock, anhydrite is a compact to fine granular substance; sometimes coarse and showing the apparently cubic cleavages of the individual grains. It may be somewhat translucent, and usually has a somewhat splintery fracture with a shimmering or pearly luster. Its color is generally white, though, like gypsum, it is often tinted reddish, yellowish, bluish, gray or dark by oxides of iron, or commingled clay, or organic matter. It is harder than gypsum but easily cut with a knife. For the other properties see description of it as a mineral. The most commonly associated minerals are rock-salt and gypsum, but locally it may contain many others, as those stated under gypsum. In the anhydrite beds in the strongly folded regions of the Alps, the clay impurity has been converted into cyanite, sillimanite, mica, etc.

The occurrence of anhydrite is similar to that of gypsum, which it frequently accompanies. It is changed on exposure to the air into that substance. The beds do not usually show any distinct stratification. In America, extensive deposits occur in Nova Scotia.

ROCK-SALT.

This is an aggregate of grains of common salt, halite or sodium chloride. It is sometimes fine, sometimes medium, and sometimes coarse grained. The color is white but it is often red or yellowish from oxides of iron, gray from intermingled clay or organic matter, and the latter may at times produce bluish or greenish tints. The properties of halite are mentioned in the chapter on rock minerals.

Associated minerals sometimes found in the salt are quartz, anhydrite and sometimes, though rarely, carbonates or pyrite.

Rock-salt occurs in geological formations of the sedimentary rocks of all ages and in many parts of the world. The beds vary greatly in thickness, from one foot to 4000 or more. Such enormous thicknesses cannot be explained by the simple concentration of an isolated body of sea-water along an arid coast-line. There must have been subsidence gradually going on; at first the less soluble gypsum, and then the salt, would be deposited, leaving a mother liquor containing the more soluble sulphates and chlorides of magnesium and potassium. If subsidence and the lowering of the barrier should now occur, there would be an influx of the lighter sea-water above, while the heavier mother liquor would flow out below and the basin would be charged anew with sea-water. If the barrier is again closed, for example by waves building it up as seen along the coast of the Carolinas, the conditions would be repeated and fresh deposits of gypsum and salt formed. Thus by repetitions of such a process we can imagine that great thicknesses of salt might be locally deposited. Finally, if no outflows occur the mother liquor is also evaporated and the more soluble salts deposited.

In the United States rock-salt occurs in beds in New York, Michigan, Louisiana, Kansas and various other states. It is found in Europe, in Germany, Austria and Poland in vast deposits; in several counties of England and in many other places. Interior drainages are present in all of the continents and in connection with them there are salt lakes and deposits of salt.

FLINT, GEYSERITE AND OTHER SILICEOUS ROCKS.

Deposition of silica, SiO_2, from its solution in water occurs both by simple concentration and evaporation and by the action of organic life. It is possible that it may also happen from chemical reactions. The deposits thus formed, while lacking the wide extent and geologic importance of the sedimentary formations produced by the processes of erosion, have yet considerable interest and may be of local significance. On account of their general similarity of composition they are here included under one heading, but the group does not include the mechanically formed siliceous sandstones. The material composing these rocks is, mineralogically, sometimes in the form of quartz — pure crystallized, SiO_2, and sometimes in the form of opal or chalcedonic silica — uncrystallized silica containing more or less water in combination as hydroxyl.

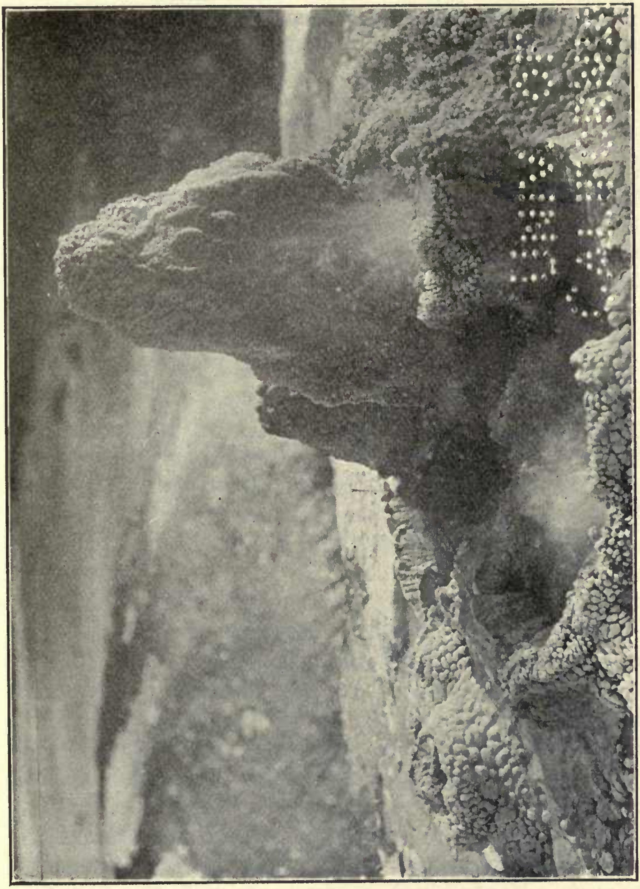
Flint. This is a dark gray or black rock, so extremely compact that it appears as a homogeneous substance. The fracture is conchoidal and the chips have a translucent edge like many felsites, which indeed it may closely resemble. The hardness is 7. It consists of an intimate mixture of quartz and opal, the coloring matter being organic and disappearing when a chip is heated before the blowpipe.

Flint is not a rock in the sense that it occurs in extended independent formations. It occurs in irregular nodules or concretions in chalk which vary widely in size, from that of a pea to extensive layers. Similarly an impure flint, occurring chiefly in limestones from the Cambrian up, is called *chert.* When these substances are studied under the microscope they are found to contain the hard siliceous parts of various organisms, chiefly of sponges and radiolarians. The matter was first derived from sea-water by such organisms, but appears secondarily to have gone into solution and been chemically deposited around certain centers, and in certain places, where favorable conditions obtained. The uses of flint for savage and prehistoric implements and weapons and for striking fire are well known. Other siliceous masses, similar in a general way to flint and chert, sometimes of the same and sometimes of uncertain origin, have received various names such as *lydianite, hornstone,* etc. *Jasper* is a chemically precipitated opaline silica. In places, as in the Lake Superior region, the jaspers are strongly ferrugineous and interlaminated with bands and streaks of hematite. They constitute rock masses of considerable size, affording valuable deposits of iron ore. They are called *jaspilite.* The cherty layers are colored bright red by the iron oxide. Another variety of these siliceous flint-like rocks are the *novaculites,* which occur in considerable beds in Arkansas, and are greatly used in the manufacture of whetstones and hones. They are very dense, conchoidal in fracture, white or pale gray in color, semi-translucent, and composed of silica. Their origin is uncertain.

Geyserite. Siliceous Sinter. In volcanic regions silica is frequently deposited by hot waters, boiling springs and geysers. Sometimes this is produced by simple evaporation and drying of the water and sometimes, as shown by Weed, it is due to vegetable organisms, *algæ,* which secrete silica from the heated waters in which they live and become coated with it. The material of the geyser cones and basins produced by drying is hard, compact, and opaline, while that formed by the plants is more or less loose, spongy, and tufaceous. If pure, it is white in color. Its formation is well illustrated in the hot spring and geyser areas of the Yellowstone Park and New Zealand (see Plate 27). The material thus formed is known as geyserite, or siliceous sinter.

Diatomaceous Earth. This is a soft, white, chalk-like, very light rock composed of innumerable microscopic shells of diatoms. The latter are excessively minute, unicelled organisms which possess free motion and are covered with a siliceous shell of great delicacy; they are considered forms of vegetable life. In waters of suitable character they may swarm in incredible numbers and their shells, accumulating at the bottom, may give rise to deposits of considerable magnitude. Some varieties of the rock are pale yellow, brown or gray. It is easily distinguished from chalk, which it may resemble, by its non-effervescing with acid; from clay by its gritty feeling, when rubbed between the fingers, and its weak argillaceous odor or the absence of it. A more positive test is the effervescence produced when it is mixed with carbonate of soda and fused before the blow-pipe. The loose, scarcely coherent material is called *infusorial earth;* when more compact it is sometimes called *tripolite.* It is extensively used for polishing purposes. Beds of considerable magnitude occur in the United States in Mary-

PLATE 27.



GEYSERITE, SPIKE SPRING, YELLOWSTONE PARK.

(U. S. Geological Survey.)

land, Virginia, Georgia and Alabama, where they are worked commercially, also in Missouri, Nevada, California and elsewhere, often as a layer in swamps which represent the fillings of former lakes. They are also found in Germany and other parts of Europe.

IRON ORE ROCKS.

The deposits of iron ore which occur as rocks, interstratified or associated with sedimentary beds, have originated through complex processes, sometimes wholly, sometimes partly, of a purely chemical nature and usually more or less influenced by the agencies of organic life. The most important set of processes has been previously mentioned but now deserves a more detailed description.

Iron exists in the original (the igneous) rocks in the form of silicates, such as biotite, olivine, pyroxene and hornblende, and also as oxides, such as magnetite, hematite and ilmenite, as disseminated grains. It also occurs in the secondary metamorphic rocks as silicates and oxides. It is also pretty generally diffused through the sedimentary rocks, in part as coloring matter and cement, and mostly in the form of ferric oxide, ferric hydroxides and ferrous carbonate. In the igneous rocks it is largely in the ferrous state and to a considerable degree also in the metamorphic ones. Also, to understand the concentration of iron and formation of iron ore rocks, it must be borne in mind that the metal forms only one carbonate, ferrous carbonate or siderite, $FeCO_3$ which, like carbonate of lime, is soluble in water containing carbon dioxide.

When the rocks are decomposed and broken down by the agencies of weathering and erosion, the silicates containing iron are altered; the ferrous oxide in them combines in part with the carbon dioxide in the circulating ground water to form ferrous carbonate which goes into solution, and in part it is oxidized to ferric oxide. The original oxides of iron react in a similar manner. The ferric oxide thus formed or liberated would be insoluble, but in the presence of decaying vegetable matter in the soil and organic acids leached downward into the rocks, deoxidation of the ferric oxide ensues; it is reduced to ferrous oxide and then becomes ferrous carbonate and goes into solution. The reason for this is that decay of organic matter is a process of oxidation, like slow combustion; the organic matter takes oxygen from the air, but in the presence of moisture and ferric oxide it will take oxygen from the latter, reducing it to the ferrous oxide which is then fitted to unite with carbon dioxide and become the carbonate.

The iron of the rocks, which is thus brought into solution, is leached out, and in standing bodies of shallow water, such as swamps, lagoons or estuaries, with small outlets to the sea, it may be concentrated and give rise to extensive deposits. Under some conditions these deposits may be of the carbonate directly, but usually the solution of the carbonate is re-oxidized, carbon dioxide escapes, and the iron is precipitated as ferric hydroxide (limonite). This oxidation is largely, if not wholly, performed by certain bacterial organisms which demand iron in their internal economy, and therefore, secrete the iron from the water, and change it in their cells from the ferrous to the ferric condition, thus rendering it insoluble. Living and dying in unimaginable numbers, though excessively minute, they give rise to large deposits.

The ferric hydroxide which is thus precipitated may accumulate on the bottom as bog iron ore, or limonite, or, as is so often the case in shallow bodies of standing water, like swamps, etc., it may again come in contact with decaying vegetable matter, and be changed back into carbonate. Such beds of iron ore may be quite pure, or they may be more or less mingled with clay and sand, brought in at times of high water, and thus impure limonites, clay ironstones, black-band ore, etc., are formed. This also explains the not infrequent association of stratified iron ore and coal beds in the same series of rocks, and the reason why in this case the iron ore is commonly ferrous carbonate.

The moving ground waters containing iron in solution, as described above, may also issue as springs and give rise to deposits of iron ore.

Certain masses of iron ore, chiefly limonite, are supposed to be residual products of weathering and solution. This is illustrated in the view that masses of limestone containing ferrous carbonate have been dissolved and carried away, but the iron, oxidized to the ferric condition in the process, has become insoluble and remaining behind has gradually concentrated. The more important iron ore rocks may now be described.

Bog Iron Ore. Limonite. This is sometimes loose and earthy, sometimes firm and porous. It consists mainly of limonite, mixed more or less with humus, phosphates, silicates of iron, clay, sand, etc. Its character has been sufficiently described under limonite among the minerals. It sometimes occurs in concretions. With increasing amounts of clay it passes over into *yellow ocher*. It is found in all parts of the world. In the United States it is widely distributed, and along the Appalachian belt, from Vermont to Alabama, deposits of limonite, most of which are probably residual in character, have furnished iron ore since the early settlement of the country, and in great quantity.

Clay Ironstone. Siderite. When reasonably pure, siderite, or spathic iron ore, is a coarse to fine crystalline aggregate of siderite grains. It is whitish to yellow, or pale brown in color, but on exposed surfaces much darker brown to black, owing to oxidation of the ferrous carbonate to limonite, or of the manganous carbonate to manganic oxides. It generally contains, more or less, carbonates of lime, magnesia and manganese. Iron pyrites or hematite are commonly associated minerals. For the properties of siderite, reference may be had to its description among the minerals.

An impure variety of siderite mixed with clay, sand and limonite in variable proportions, of a compact appearance, and generally of dull brown colors, is known as clay ironstone. It is apt to occur in nodules, often as concretions around some fossil, and lenticular masses which increase until they become interstratified beds of considerable thickness. Another variety which contains so much organic, coaly matter that it is colored black is known as *black-band* ore. It is especially associated in the strata with coal beds from the Carboniferous upward.

Carbonate ores of iron are of less importance in the United States than the deposits of limonite and hematite. They occur in Pennsylvania, Ohio and Kentucky, of Carboniferous age, and in the Lake Superior region in Michigan and Minnesota, of Algonkian age. They occur in Europe in England, Germany, France and Spain, in deposits of great technical value. Black-band is found in the coal-bearing strata of Pennsylvania, England, etc.

Hematite. Red Iron Ore. This occurs in the form of veins, lenticular masses and beds, in various geological formations and especially in those whose strata have been folded. As a rock, it varies from fine grained and compact to earthy or fibrous, is of a red to brown color or, where crystalline, of a dark gray. Its properties as a mineral have been previously given. It occurs pure or nearly so, but with varying mixtures of clay, sand or silica, it passes insensibly into ferrugineous clays, red ochers, or shales, sandstones, cherts, etc. In this connection see jaspilite under flint. While hematite undoubtedly occurs as a normal sedimentary or stratified rock, interbedded with other unchanged strata, as in the beds which have such a wide distribution in the eastern United States in the Clinton group of the Niagara period, it is more generally to be considered a metamorphic rock, and as such, might be included among the metamorphic iron rocks described in Chapter XI, such as itabirite and hematite schists.

Extensive deposits of hematite are found in various parts of the United States and Canada. The greatest amounts mined as ore come from Tennessee and the Lake Superior Region, the vast production in the latter leading the world in output. Large beds are also found in England and other parts of Europe.

Iron Oölite. The iron rocks described above, and especially red hematite, not infrequently assume a concretionary form in which the rock is composed of rounded, sometimes polygonal, grains which vary in size from that of fine sand to peas. An examination of them shows that they have a concentric shelly structure. The color varies from red to brown. Sometimes the rock is composed of them alone and sometimes they are thickly embedded in a marly or clayey cement. The iron ore appears in many cases to have been deposited around grains of sand, fragments of fossils, etc., as neuclei. The Clinton ores mentioned above frequently assume this oölitic character and it is well known from various European localities. Such ores have sometimes been changed into magnetite while still retaining the oölitic structure.

LIMESTONE AND OTHER CARBONATE ROCKS.

This group of rocks has the common property of being composed of carbonate of lime, calcite, $CaCO_3$, or of this substance intermingled more or less with dolomite, $MgCa(CO_3)_2$. It is also a common property that, so far as known, the carbonate of lime has primarily been separated from water, rendered insoluble and accumulated by the action of living organisms of one kind or another. Secondarily, the deposits thus made may be mechanically broken up and redeposited, or they may be taken into solution, carried away and precipitated elsewhere. There may be some possible exceptions to this rule, that the carbonate of lime is primarily precipitated by organisms, in the cases where it is concentrated in alkaline lakes by inflowing waters and finally deposited, or in the evaporation of shut-off portions of the sea, but these are of small account and negligible in comparison with the great formations produced by life agencies.

Hence it is generally held that the great masses of carbonate rocks, even when they do not contain fossils, are a proof of the existence of life at the time of their original deposition.

This group of rocks is soluble in hydrochloric acid; entirely so when pure carbonates, but generally leaving more or less of a residue, consisting chiefly of sand, clay, silica, etc. In some cases, where dolomite is present, the acid must be heated. Their hardness is less than 4, hence they may be readily scratched or cut with the knife.

The following are the important members of the group.

Limestone. This is the most common and important carbonate rock. It is fine grained to very dense in texture and its color varies from whitish, through tones of yellowish to brown, or from various shades of gray, dove-color, bluish-gray, dark-gray to black. It is rarely of reddish colors. The yellow and brown colors are due to iron oxide, the gray and black to organic matter. The gray colors are most common. Compact varieties have an even to somewhat conchoidal fracture. It effervesces freely with any common acid, with vinegar (acetic acid) or lemon juice (citric acid). It is easily scratched with the knife and many of the less compact varieties are friable to the finger nail. The specific gravity varies from 2.6–2.8. On exposed surfaces it is apt to be cavernous and often tinted or blotched reddish or yellowish from oxidation of small amounts of ferrous carbonate it may contain. It occurs in individual beds of all thicknesses up to 100 feet or more.

Some limestones consist of pure grains of calcite, others possess a fine, clay-like cement between them. Accessory minerals, which are sometimes seen, are pyrite and quartz, the latter in minute crystals, sometimes lining cavities.

In following analyses I, II, and III are of very pure limestones; IV is an impure type containing considerable dolomite and sand and clay. Such transitions through impurities are common; thus V for example shows one toward the clay-ironstone previously described. Transitions to dolomite are not common; an examination of a large number of analyses shows that generally either the rock contains very little or no magnesia, or it has much and is a regular dolomite as described later.

<table>
<tr><th></th><th>SiO_2</th><th>Al_2O_3</th><th>Fe_2O_3</th><th>FeO</th><th>MgO</th><th>CaO</th><th>H_2O</th><th>XyO</th><th>CO_2</th><th>Total</th></tr>
<tr><td>I....</td><td>0.4</td><td>–</td><td>0.4</td><td>–</td><td>trace</td><td>54.8</td><td>1.1</td><td>–</td><td>42.7</td><td>99.4</td></tr>
<tr><td>II...</td><td>0.6</td><td>–</td><td>0.4</td><td>–</td><td>0.4</td><td>54.2</td><td>–</td><td>–</td><td>44.0</td><td>99.6</td></tr>
<tr><td>III..</td><td>1.2</td><td>0.2</td><td>0.2</td><td>0.3</td><td>0.6</td><td>53.8</td><td>0.9</td><td>0.1</td><td>42.7</td><td>100.0</td></tr>
<tr><td>IV..</td><td>7.0</td><td colspan="2">3.6</td><td>–</td><td>9.0</td><td>39.3</td><td>0.2</td><td>1.2</td><td>38.8</td><td>99.1</td></tr>
<tr><td>V...</td><td>3.2</td><td>0.1</td><td>10.9</td><td>15.2</td><td>11.0</td><td>26.6</td><td>0.5</td><td>1.5</td><td>41.1</td><td>100.1</td></tr>
</table>

I, Trenton Limestone, Lexington, Virginia; II, Buff Limestone, Hoosier Quarry, Bedford, Indiana; III, Lithographic Limestone, Solenhofen, Bavaria; IV, Impure dolomitic Limestone, Greason, Pennsylvania; V, Sideritic-dolomitic Limestone, Gogebic dist., Michigan.

XyO represents small quantities of organic matter, manganese oxide, etc.

The strength of limestone as a rock varies very much with the texture; that of firm compact varieties is very high while loose porous ones are very weak. Thus a dense variety has been shown to have a crushing strength of over 40,000 pounds per square inch, while others scarcely exceed 3000 pounds per square inch. The well known white oölitic limestone of Bedford, Indiana, has an average crushing strength of 4300 pounds. Any good firm and compact limestone has a strength far in excess of any load that it may be called upon to endure in modern structures. The porosity of limestones varies considerably; those containing the most sand are usually the most porous; the ratio of pore space to rock volume may vary from 15 per cent to practically nothing, the ratio of the weight of water it can absorb to the weight of rock is in general much less than this, usually not more than one-half as much.

There are many varieties of limestone, depending on circumstances, especially the mode of formation. Thus in some there are abundant remains of fossils which may give the rock a distinctive character. These comprise a great variety of organisms, among which may be mentioned corals, crinoids, shells of mollusks, brachiopods, gastropods, foraminifera, remains of sponges, etc. The "encrinal limestone" of Silurian age in western New York is an example. Sometimes these fossils occur in such numbers that the entire rock is composed of masses of shells, or the hard part of one particular organism, with just enough fine carbonate of lime between them to act as a cement. Examples of this are seen in the layers composed wholly of brachiopod shells found in the Niagara formation of the Silurian in western New York. Such rocks are sometimes called "shell limestones." Certain limestones composed of corals are also examples of the same thing.

On the other hand, there are varieties which depend on the presence of some impurity which gives a particular character to the rock. Thus it may contain much clay and is termed an *argillaceous limestone* or it may contain much sand of siliceous character and be an *arenaceous limestone:* such rocks are transitional to shales and sandstones. Others which are dark colored may yield a strong, disagreeable, bituminous odor when struck and broken and are called *bituminous limestones;* they contain considerable organic matter. In some, which are termed *glauconitic limestone,* the rock is more or less filled with green grains of glauconite. *Lithographic* stone is a fine, compact, somewhat schistose limestone; the flesh-colored rock from Solenhofen, Bavaria, remarkable for the well preserved fossils it occasionally contains, is especially used for this purpose. It is a very pure limestone, as shown by the analysis given above.

Limestones are very apt to contain concretions and masses of chert, or hornstone, of the character described in a previous section; they often become so abundant as to form definite bands or layers in the rock.

By the weathering of limestones the lime carbonate is removed in solution, leaving the insoluble impurities behind. These form clays or loams which are colored deeply red or yellow by the oxidation of the iron minerals originally present, and commonly contain pebbles of chert or quartzose material and masses of limonite. Such residual soils are commonly very fertile and cover large areas in the southern United States, and in other parts of the world.

Uses of Limestone. The use of limestone for structural purposes of all kinds is well known and needs no further comment. The same is true of its manufacture, by burning, into quicklime for mortar and cements. Large quantities are also used as a flux in smelting operations, as in the making of iron and steel. In recent years the use of certain impure limestones containing 15–40 per cent of clay, or other substances consisting of silica, alumina and iron oxide, in the manufacture of natural hydraulic cements has risen to very large proportions.

Dolomite. The geological use of this term is not always the same as the chemical one. Chemically, or mineralogically, by dolomite is meant a chemical compound of a definite composition $CaMg(CO_3)_2$ with CaO, 30.4 per cent, MgO 21.7, CO_2 47.8, while geologically the term is used for any limestone which consists dominantly of this compound, although it may also contain a large amount of admixed calcite, $CaCO_3$, and in some parts of Europe it is employed to designate limestones of a particular geological period, some of which are not dolomites at all.

The description of the colors, texture, and other physical characters of limestone given above, applies equally well to dolomite. In fact it cannot ordinarily be told in the field, or by mere inspection of a hand specimen of a rock, whether it is a dolomite or a pure limestone.

Dolomite is somewhat harder than true limestone and if it is a pure dolomite it will not dissolve with effervescence in acetic acid (vinegar) and but very slowly in cold hydrochloric; if it contains admixed calcite this reacts very readily. The best test is a chemical one for magnesia in a solution obtained by boiling the powdered rock in dilute hydrochloric acid.

The following analyses show the chemical composition of some examples of this rock.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	CO_2	H_2O	XyO	Total
I....	3.2	0.2	0.2	0.1	20.8	29.6	45.5	0.3	—	99.9
II...	3.1	—	0.1	0.9	20.0	29.7	45.3	0.3	0.2	99.6
III..	1.1	0.4	—	—	19.9	31.5	45.6	1.3	0.1	99.9
IV ..	5.0	1.0	0.5	—	16.8	32.2	43.8	—	—	99.3

I, Knox Dolomite, Morrisville, Alabama; II, Dolomite, Sunday Lake, Gogebic district, Michigan; III, Dolomite, Tornado Mine, Black Hills, South Dakota; IV, Dolomite (magnesian limestone), Newcastle, England.

The origin of dolomite is a matter which has been much discussed and many theories have been propounded by geologists and chemists in explanation of it. When all the facts are taken into consideration, it is clear that dolomite is not an original rock, but has been formed from pure limestones by the substitution of a part of the lime by magnesia, from waters containing magnesium salts in solution. Dolomite is a denser and more stable compound than calcite; if the latter were subjected to the action of soluble magnesium salts there would be a constant tendency for dolomite to form and part of the lime to be liberated, as illustrated in the following reaction,

$$2\,CaCO_3 + MgCl_2 = CaMg\,(CO_3)_2 + CaCl_2.$$

It is evident that if the magnesia solution was strongly concentrated the exchange, in a given mass of limestone, would be effected more quickly. If the solution were heated it would also act more quickly; if it acted under pressure the result would also be hastened, and, finally, as time is an important element, the longer the limestones have been subjected to the solutions the more completely we may expect them to be changed to dolomite. If we consider in addition, that not only sea-water contains magnesium salts, but also the circulating ground waters and thermal waters ascending from the depths, in greater or lesser amount, it is clear that in harmony with the above principles, the change, which we may call *dolomitization*, must take place in a variety of ways and under various conditions, not only in the sea, but also on the land; that all limestones are not converted completely into dolomite before they emerge from the sea must be due to certain reasons; that the solution is too dilute, that it is not hot enough, that there has not been sufficient time, that the deposits are too compact to permit sufficient penetration and circulation of sea-water, etc. But if lime deposits are subjected in an enclosed basin to constantly concentrating sea-water they may become more rapidly converted. This might happen, for instance, if a coral atoll were somewhat elevated and its lagoon wholly or nearly shut off from access to the sea. The formation of dolomite in such enclosed basins of sea-water would also explain its frequent association with gypsum and anhydrite. The application of the principles stated above would also lead us to conclude, that the older and more deeply buried a limestone was, the more apt it would be to become a dolomite; that in disturbed and folded mountain regions, limestones of the same age and formation would be more likely to be dolomitic than those of undisturbed areas, because the rocks are there more fractured and filled with thermal solutions, and in practice the facts are found to confirm these views. The connection with thermal waters also explains the frequent association with lead and zinc ores.

The mineral dolomite is denser than calcite and in the change above mentioned a considerable reduction of volume, amounting to 12 per cent, must occur in the limestone. This would apparently help to explain why dolomites are so frequently very porous or cavernous rocks, though if deeply buried, all such cavities would be closed by the pressure.

Limestones and dolomites are rocks of such general distribution in all parts of the world where stratified rocks are found, that their occurrence needs no special mention.

Oölite. Oölitic Limestone. This is a well-characterized variety of limestone, which consists of minute to small spherical concretions, presenting very much the aspect of a fish roe, whence the name from the Greek, meaning egg-stone. The round grains vary in size from very minute up to those as large as a pea. In the larger ones it may often be observed that they have a concentric shelly structure and thus consist of successive coats. An illustration of a coarse oölite or pisolitic limestone from Bohemia is shown on Plate 28. There is usually more or less limy cement binding the grains together.

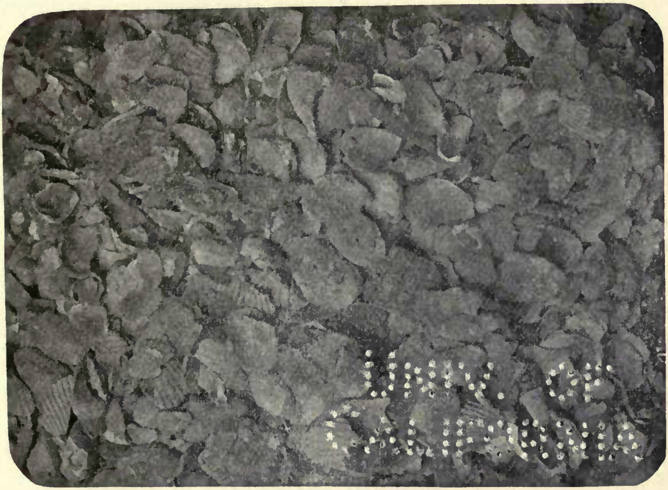
Examination of oölites generally shows that some object, such as a bit of shell, a grain of sand or something similar, has served as a nucleus around which the coatings of lime carbonate have accumulated. On the shores of Great Salt Lake at the present time oölitic sands are forming from the waters which are charged with lime and other salts in solution. As the particles are rolled on the beach, or agitated in the water, all parts become equally coated and the spherical form is assumed. By a similar process oölitic grains are forming in springs charged with lime salts, as at Carlsbad in Bohemia. The concretionary structure is best seen under the microscope; it is rarely sufficiently coarse to be observed with the eye alone, but may be sometimes made out with a lens. Oölitic limestones constitute large and important formations, often of great thickness and of different geological ages. They are especially important in the Jurassic strata of England and elsewhere in Europe. It is a structure also assumed by some American limestones.

Chalk. Typical chalk is a soft, white, friable rock, whose use for marking and blackboard crayons is well known. While generally pure white it may sometimes be tinted gray, flesh color, or buff. It consists of a fine calcareous powder, which by examination under the microscope has been found to consist of the tiny shells of foraminifera, mingled with minute fragments of the shells and hard parts of various organisms, as well as the siliceous spicules of sponges, shells of diatoms and radiolarians, together with occasional microscopic fragments of various minerals. It is the siliceous material of the sponge spicules, diatom shells, etc., that has concentrated into the nodules and concretions of flint, so commonly found in certain beds of chalk, and whose analogue is seen in the layers and masses of chert in limestones. Chalks, in spite of their fine grain, are very porous rocks, absorbing as much water as 20 per cent of their weight in some cases.

Chemically, chalks are quite pure carbonate of lime, as

PLATE 28.

A. OÖLITE, VARIETY PISOLITE, BOHEMIA.



B. COQUINA, FLORIDA.

shown in the following analyses of three specimens given by different authorities.

It has been customary to consider chalk a formation produced on the bottom of the deep sea, from its resemblance to the calcareous oozes or muds found underlying the depths of modern oceans. It has evidently not always been formed in this way, as shown by the fossils indicative of shallow water which some chalks contain, as well as the perfect skeletons of birds, pterosaurs and other vertebrate animals. The facts in some cases would point rather to its having been formed in clear, warm and shallow seas, free from the products of land waste.

Closely related to chalk, but differing in the fact that they do not predominantly consist of foraminiferal shells, are light, chalky, earthy limestones formed in a variety of ways, such as from coral sands and muds; from those materials accumulated by the wind on coral islands; from ground-up shells in clear, shallow seas, etc. A whitish, fragile rock formed on the coasts of Florida, which consists of shells and their fragments of all sizes somewhat lightly compressed and cemented together, is known as *Coquina*, from the Spanish word for shell. (See Plate 28.)

	$CaCO_3$	$MgCO_3$	SiO_2	$(FeAl)_2O_3$	H_2O	Total
I.....	94.2	1.4	3.5	1.4	0.5	101.0
II....	96.4	1.4	1.6	0.4	0.2	100.0
III...	98.4	0.1	1.1	0.4	—	100.0

I, White chalk, White Cliffs, Little River, Arkansas; II, Lower Cretaceous chalk, Burnet Co., Texas; III., White chalk, Shoreham, Sussex Co., England.

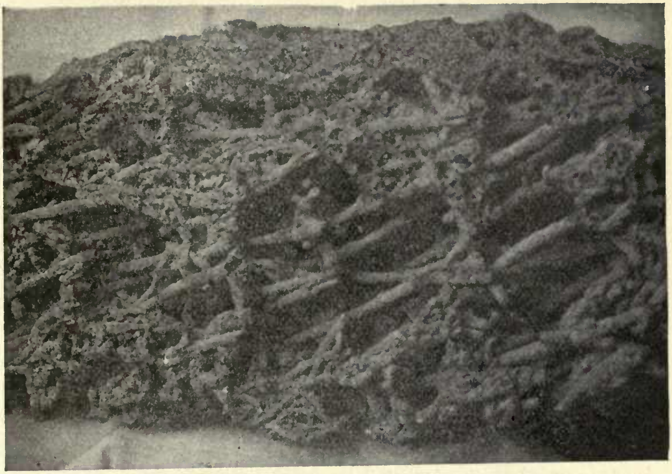
Chalk is found extensively in Europe in England, Germany, France, etc., where its occurrence is the result of a distinct geologic epoch, named on this account the Cretaceous. It also occurs widely distributed in the Cretaceous formations of the southern trans-Mississippi States, in Nebraska, Arkansas, and especially in Texas.

Travertine, Calcareous Tufa. In the preceding chapter it was shown how material of the land surface is taken into solution and carried into the sea. This is especially important with regard to lime, which goes to the sea as a sulphate and carbonate, the latter being much the more momentous. This lime carbonate comes, not only from pre-existent carbonate rocks, but also from the lime silicate minerals of the igneous and metamorphic ones, which under atmospheric agencies are converted into carbonates. The lime carbonate on its way to the sea may be temporarily deposited, giving rise to rock-masses of some magnitude and importance.

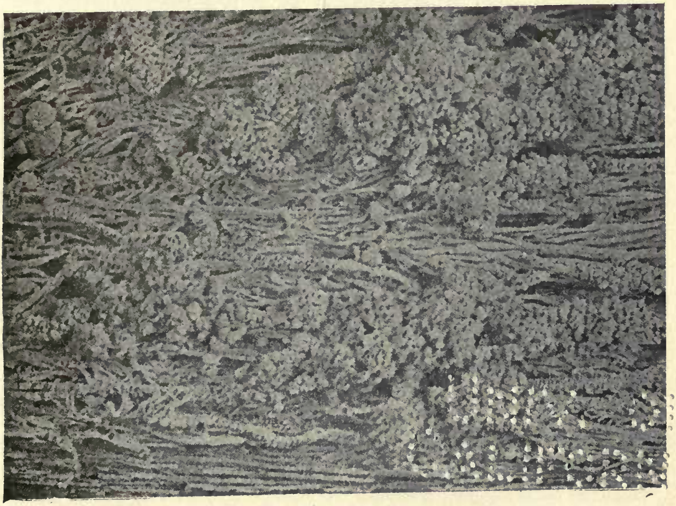
Carbonate of lime has little solubility in pure water, but if the latter contains carbon dioxide, the lime carbonate is converted into a soluble bicarbonate and the amount of the latter formed and taken into solution depends on the amount of carbon dioxide present. Thus in regions where limestones or other carbonate rocks abound, the natural waters, under atmospheric pressures, attack such rocks and take the lime carbonate into solution in a relatively slow manner, but in spring waters, and especially thermal ones coming from depths, the pressure may be great, the amount of contained carbon dioxide large and the quantity of dissolved carbonate of lime proportionately so. Such waters on coming to the surface lose the greater part of the dissolved carbonic acid in the form of gas, and the lime in solution is consequently deposited rapidly and in large amount. In the waters under surface atmospheric pressure the lime is deposited by evaporation and therefore much more slowly. In warm waters the deposit of lime may be much increased by the action of low forms of vegetable life, *algae,* living in them, which secrete lime from the water.

The rock thus formed by deposit of carbonate of lime from solution is called *travertine,* from the old Roman name of the town of Tivoli near Rome, where an extensive formation of the substance exists. When deposited slowly, as in the stalactites and stalagmites in caves, it is rather hard and compact, fine crystalline, sometimes white but usually tinted yellowish or brownish; it often has a fibrous or concentric structure; it breaks with a

PLATE 29.



A. CALCAREOUS TUFA, DEPOSITED ON VEGETATION, COLORADO.



B. CALCAREOUS TUFA, YELLOWSTONE PARK.

(U. S. Geological Survey.)

splintery fracture. When deposited more rapidly, as by springs, it is softer, not evidently crystalline, and porous to loose or earthy; when formed coating vegetation it may be open, cellular, spongy, bladed or moss-like, as illustrated in Plate 29.

These looser, less compact, varieties are commonly called *calcareous tufa* or *calcareous sinter*. Deposits of travertine, or calcareous tufa, are found in nearly all countries and especially in limestone regions. Many caves are celebrated for the number, size and beauty of the stalactitic and stalagmitic formations they contain. See Plate 30. Springs depositing carbonate of lime are very common, but warm carbonated waters are chiefly found in volcanic regions or those which have recently been so, like the celebrated Mammoth Hot Springs of the Yellowstone Park, and others found in California, Mexico, Italy, New Zealand, etc. See Plate 31. The so-called Mexican "onyx" or "onyx marble," which is extensively used as an ornamental stone, is a travertine with a banded structure, beautifully brought out by its varied tinting through metallic oxides.

Marl. This name is given to loose, earthy or friable deposits consisting chiefly of intermingled carbonate of lime, or dolomite, with clay, in variable proportions. The color is usually gray, but they are often yellow, green, blue or black, and sometimes with pronounced color tones due to some special substance, as oxide of iron or organic matter. They show all gradations into clays and shales. On exposure to the air or water they crumble quickly into coarse soils. The carbonates in them are readily detected by their effervescence in acid. According to special substances or objects, which they may contain in addition to those mentioned, different varieties are named; thus *sandy marl* is full of grains of quartz sand and often of other minerals; *shell marl* is a whitish, earthy deposit formed of fragments of shells of various organisms formed in enclosed basins of water, mingled with clay, etc. In the Atlantic and Southern states this name is applied to beds which contain abundantly shells of mollusks, gastropods and other shell-fish.

The chemical composition of marls varies very greatly; the following analysis of a compact one from Colorado will serve as an example.

$CaCO_3$	$MgCO_3$	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	H_2O	Org. Sub.	XyO	Total
21.6	1.7	45.9	13.2	3.9	1.3	2.3	5.4	3.5	1.2	100.0

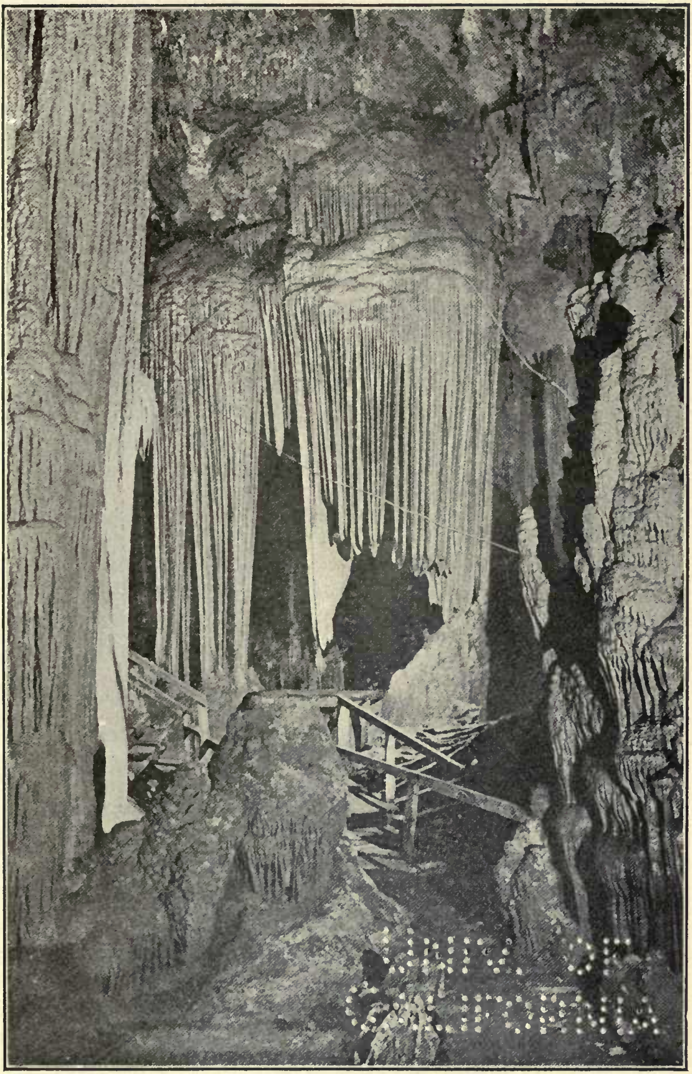
XyO = small quantities of TiO_2, Na_2O and P_2O_5.

Greensand Marl is described under sandstones.

PHOSPHORITE — PHOSPHATE ROCKS.

Deposits of phosphate of lime, while not of great geological importance in making extensive formations, are yet of considerable interest and, commercially, of great value, from their use as soil fertilizers. When occurring in stratified rocks and unconnected with igneous intrusion they represent material of organic origin. While some invertebrates, such as a few species of brachiopods, secrete phosphate of lime in their shells and hard parts, it is mostly to the bones and excrement of vertebrates that the origin of this material must be ascribed. Sometimes the deposit appears to be the direct and original one, but more commonly it is secondary in nature, in that the phosphates have been leached out, carried down and redeposited as nodular, concretionary or lenticular masses in clefts and other cavities in the rocks in which they occur. Especially in limestones, which, being soluble, are carried away, the less soluble phosphatic material tends to accumulate in such masses. The general name of phosphate rock or *phosphorite* may be used for all such material. The appearance of these rocks is variable, sometimes com-

PLATE 30.



STALACTITES OF TRAVERTINE IN LURAY CAVERN, VIRGINIA.

(U. S. Geological Survey.)

pact semi-crystalline, fibrous or concretionary, often cavernous or spongy; sometimes in rounded mammillary forms; in other cases more or less earthy. The color is usually gray, but sometimes white, buff, reddish, bluish, or even black. The simplest test for these phosphates is to dissolve a powdered sample in nitric acid, and, after filtering off the insoluble matter, to add an excess of ammonium molybdate solution and ascertain by the yellow precipitate if phosphorus is present. The general chemical composition is shown in the following analyses of samples from various localities in North Carolina.

Sand and insoluble matter	1.5	31.2	22.1	23.4
Carbonate of lime	12.0	15.9	42.1	64.3
Phosphate of lime	71.8	42.1	20.5	11.2
Water and other constituents	14.7	10.8	15.3	1.1
Total	100.0	100.0	100.0	100.0

Phosphorites are widely distributed; in the United States they are found extensively in the Carolinas, in Florida, in Tennessee, and in some of the other states; they occur in England and Wales, in Belgium, northern France, and Russia.

COAL AND OTHER CARBONACEOUS ROCKS.

It is well known that, interbedded with other stratified rocks of the different geological periods down to the present, there occur layers of carbonaceous character, which under the names of coal, lignite, etc., represent the remains of former vegetable life, which once flourished where these beds are now found. The formation of peat in modern lakes, swamps, and bogs, and its occurrence in beds interstratified in recent delta deposits with those of sands and clays, as in the Mississippi delta, shows us how these beds of coal were formed. For between the growing vegetation of to-day, its change into peat, from this into lignite or brown coal, and so on into bituminous coal, then into anthracite, and eventually into graphite or practically pure carbon, every step of gradual transition can be traced.

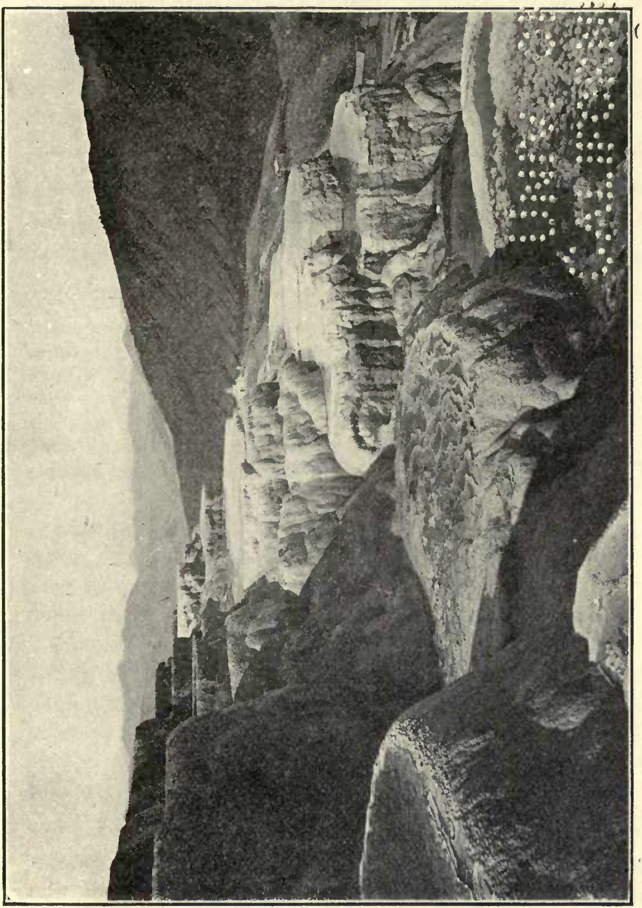
The vegetable matter composing plants consists for the most part of carbon, hydrogen, and oxygen. Its decay in the air, like combustion, is a process of oxidation; the hydrogen goes off as water, the carbon as carbon dioxide, the oxygen of the air assisting that in the vegetable matter to effect the change. In this process most of the carbon is removed. If the decay takes place under water, however, the access of the oxygen of the air is prevented and the process becomes much like that where wood is burned with a limited amount of air to form charcoal. Some of the carbon unites with some of the oxygen to form carbon dioxide; some of the hydrogen unites with the rest of the oxygen to form water; the rest of the hydrogen unites with some of the carbon to form marsh gas (methane) and the remainder of the carbon is left behind. This can be illustrated by the following equation in which the formula of cellulose, which comprises the most important part of vegetable matter, is used.

$$\underset{\text{Cellulose}}{C_6H_{10}O_5} = \underset{\text{Carb. Diox.}}{CO_2} + \underset{\text{Water}}{3H_2O} + \underset{\text{Methane}}{CH_4} + \underset{\text{Carbon}}{4C}.$$

It is not intended to imply that this change takes place at once, or is complete, under water; it goes on gradually, and as the CO_2 and CH_4 are evolved, the residual matter becomes richer in carbon and poorer in hydrogen and oxygen. Thus vegetable matter is converted into peat and this by compression and further change into brown coal or lignite. The same process goes on in coal beds, furnishing the deadly gases known to the miners as choke-damp (CO_2) and fire-damp (CH_4), and lignite thus changes to bituminous coal. Folding of the strata, with compression and heat, and the consequent rupturing and fissuring of the overlying beds, which permits the easy escape of the gases, hastens the process, and under such circumstances the coal is changed to anthracite, which is much richer in carbon, or even into graphitic coal which is practically pure carbon. Thus the degree to which lignite has advanced through bituminous coal to anthracite depends in part on its geological age, and in part on the conditions to which it has been subjected.

Peat. This varies from a brown to yellowish matted mass of interlaced fibrous material, strongly resembling compressed tobacco, in which remains of plant leaves,

PLATE 31.



TRAVERTINE BASINS, MAMMOTH HOT-SPRINGS, YELLOWSTONE PARK.

stems, roots, etc., are still recognizable, in the upper portion of the bed, to a dark brown, or black, compact, homogeneous mass appearing much like dark clay when wet, in the deeper, lower parts. A dried, compact, very pure peat from Germany is stated to have the following composition:

Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Ash.	Total.
55.9	5.8	36.4	1.0	0.9	100.0

Under enormous pressure it has been found that peat may be artificially converted into a hard, black substance like coal. The wide distribution of peat and its use as a fuel are too well known to need further mention. Its purity depends on the amount of clay and sand mingled with it in the process of formation; even the purest peat, like coal, has a small percentage of ash resulting from the mineral constituents in the plants.

Lignite. Brown Coal. Usually a chocolate brown in color, but varying to yellowish or black; compact and firm to earthy and fragile; luster dull and soft to pitchy; often shows distinctly the texture and grain of wood or intermatting of vegetable fibers. Hardness varies from 1–2.5, the specific gravity from 0.7–1.5. It burns readily with a smoky yellow flame, and strong odor. The carbon in it varies from 55 to 75 per cent. A lignite from Germany is stated to have the following composition which will serve as an illustration.

Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Ash.	Total.
57.1	4.6	36.0	0.2	2.0	99.9

Lignite belongs in the Cretaceous and Tertiary formations and often forms considerable beds where these formations occur. It is found in small amount in the eastern United States in the Tertiary at Brandon, Vermont, but in the Cretaceous deposits of the Rocky Mountain states, and in the Dakotas it occurs in large and valuable fields. It is found also on the Pacific Coast, and in Germany in Europe; and elsewhere. Where better coal is not to be had it frequently furnishes a valuable fuel.

Bituminous or Soft Coal. This is a compact, brittle rock of a gray-black to velvet-black color. It has a lamellar, conchoidal or splintery fracture; sometimes more or less cubical. The luster varies from dull to pitchy; the specific gravity from 1.2–1.5. It gives a black to brownish-black streak. It burns with a yellow flame and gives a strong bituminous odor. It often shows distinct stratification through the varying luster of the different layers. Generally there are no traces of organic structures visible to the eye. Some varieties fuse or sinter together on heating, leaving a coherent residue or coke, and are thus called coking coals; others fail to do this and fall to powder. The amount of carbon in a soft coal varies from 75–90 per cent. A coking coal from Northumberland in England has been found to have the following composition.

Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Sulphur.	Ash.	Total.
78.7	6.0	10.1	2.4	1.5	1.4	100.1

The sulphur in coal comes from pyrite, which is a very common impurity. Bituminous coals vary considerably in the relative proportions of fixed carbon to volatile matter, that is in the proportion of the carbon left behind on heating to the gases, tar, etc., driven off; the latter may be as much as 30–40 per cent and such coals are called fat coals and are used for the making of gas, coke, etc. Those with 15–20 per cent volatile matter are largely used for steam engines and are often called steam coals. They are transitional to anthracite.

In addition to ordinary coal there are, depending on the physical characters, a number of varieties which are well recognized. Thus *cannel coal* is a dense, lusterless, highly bituminous form without structure and generally showing conchoidal fracture. *Jet* is somewhat similar but characterized by its high luster, intense black color, asphaltic appearance, and toughness, which permits of its being readily turned and worked. Its use in mourning jewelry, buttons, ornaments, etc., is well known. It occurs in small, scattered, isolated masses in the later formations in various places, one of the chief localities being at Whitby in Yorkshire, England. It is regarded by some as representing water-logged fragments of originally coniferous wood. Bituminous coal occurs in North America in Nova Scotia; in the Appalachian coal field of western Pennsylvania, Ohio, West Virginia, Kentucky, Tennessee, Alabama and Georgia; the Central coal field of Illinois, Indiana and Kentucky; in Michigan; the Western field of Iowa, Missouri, Kansas, Arkansas, Oklahoma and Texas. These are of Carboniferous age. In the Rocky Mountain states and on the Pacific coast there are also large deposits of Cretaceous and Tertiary age. Elsewhere, in England, Belgium, Germany, France and Russia, in South Africa, Australia, India and China, this coal occurs and is mined in quantities. It is the chief coal of the world, and the enormous increase in production in these later years (in the United States from 137,000,000 tons in 1896 to 463,000,000 tons in 1922) points in no uncertain way to its exhaustion in a not distant future.

Anthracite. Hard Coal. This is a compact, dense rock, iron-black to velvet-black in color. It is brittle; has a strong vitreous to sub-metallic luster, a more or less pronounced conchoidal fracture, and a hardness of 2–2.5. Specific gravity 1.4–1.8. Anthracites vary in the amount of carbon they contain from 80–95 per cent; Pennsylvania varieties from 85–93 and of Wales 88–95. The amount of fixed carbon varies from 80–90 per cent; the volatile hydrocarbons generally do not much exceed 5 per cent and the remainder consists of moisture and ash. An analysis of a Welsh anthracite is given as:

Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash	Total
90.4	3.3	3.0	0.8	0.9	1.6 =	100.0

Anthracite requires a strong heat for ignition and with abundant access of air burns with a pale blue flame, giving great heat without smoke or odor. These qualities, with its relative cleanliness, particularly adapt it to household purposes. Some anthracites exhibit on broken surfaces a strong play of spectrum colors produced by iridescent films and are called " peacock " coal.

Anthracite occurs not only in regions of folded strata as previously stated, but also, though usually in no great quantity, where beds containing ordinary bituminous coal or lignite have been invaded by intrusive masses of igneous rock, as in New Mexico, Colorado, Montana and Scotland. The largest and most important deposits of anthracite are those of eastern Pennsylvania, a considerable part of which has been already mined. It occurs also in Wales, Belgium, France, Russia, and in the province of Shansi in China, as well as in other places.

In addition to the carbonaceous rocks described above, other carbonaceous and sometimes combustible substances occur, such as graphite, ozokerite or mineral wax, asphalt and various modifications of it, petroleum, etc., but not in such a manner or relation that they may be properly included in a work treating solely of rocks. Also between the coals and the sandstones and shales, intermediate types exist in great variety, but these are best treated under the description of the latter rocks.

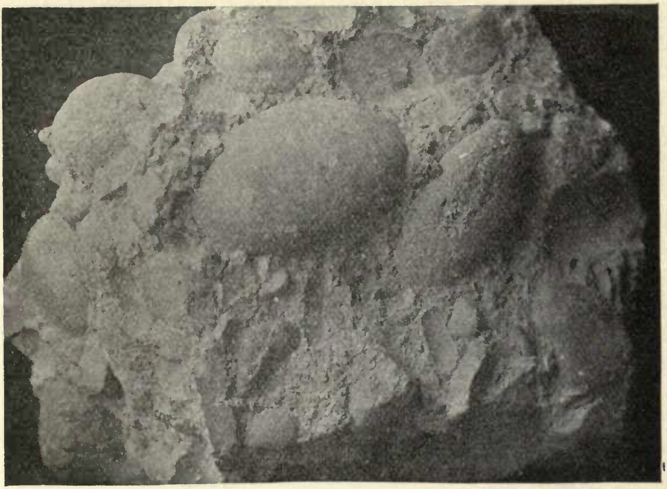
Sedimentary Deposits of Mechanical Origin.

These include the products of land waste by various erosive agencies, which have been laid down in stratified form, by moving currents of water in seas, lakes, and on the flood-plains of rivers, and afterwards consolidated into rocks, as described in the foregoing chapter. According to the size of the particles they are divided into the gravel rocks or *conglomerates* and *breccias,* into the sand rocks or *sandstones,* and into the mud or clay rocks, or *shales,* as previously mentioned.

CONGLOMERATES AND BRECCIAS.

Conglomerates. These consist of pebbles of various sizes, intermingled with a finer material which acts as a cement. The pebbles may vary from the size of a pea up to large boulders. They are rounded by the action of

PLATE 32



A. CONGLOMERATE, OF SEDIMENTARY ORIGIN.

UNIV. OF CALIFORNIA

B. BRECCIA, OF SEDIMENTARY ORIGIN.

water. They may consist of any kind of rock, though generally of the harder and more resistant varieties, or they may be of a simple mineral, usually quartz or feldspar. The pebbles may be all of one kind or of a mixture of several kinds of rocks or minerals. The cementing material may also vary greatly; it may be composed chiefly of consolidated sand, either purely siliceous or mixed substances; it may be calcareous in nature, or chiefly composed of clay, or of these substances largely mingled with iron oxide. There may be a sharp distinction between the relatively large pebbles, and the very fine matrix in which they are enclosed, and if this contrast is pronounced and the matrix present in considerable amount, such conglomerates are often called *pudding stone*. On the other hand there may be gradations in size from the pebbles down into the matrix. There is of course great variation in the color of these rocks; in some cases the pebbles are sharply defined by their colors from the matrix; in other cases the rock may have one general hue, alike for pebbles and matrix — this is more apt to be the case where the rock has been somewhat changed or altered from its original character.

Breccias. In a breccia the fragments which correspond to the pebbles of a conglomerate, instead of being rounded, are sharp and angular in character. (See Plate 32.) This indicates, if the material has been laid down in water, that they have suffered very little transport and are close to their place of origin. In other respects what has been said in regard to conglomerates will also apply to breccias.

Conglomerates and breccias, which are composed of a single type of rock, are generally called by its name and we thus have quartzite conglomerates and breccias, limestone conglomerates and breccias, etc. Volcanic breccias, produced by the fragmental accumulations of eruptive activity, are really igneous rocks and have been already described (see page 269). The material may, however, fall into water and be rounded, assorted, and stratified, giving rise to *volcanic conglomerates;* such rocks are very difficult, and sometimes impossible, to distinguish from conglomerates formed by the erosion of such land areas as are formed for the most part of surface extrusions of lavas.

Breccias are sometimes produced as the result of the breakage and grinding of the rock masses along some fault plane upon which powerful movement is occurring. The fragments thus formed may be afterwards cemented together into firm rock by deposits from solutions circulating in the zone of crushed and broken rock. Such types are called *friction breccias* and they naturally show no evidence of stratification.

Conglomerates are normally formed from deposits laid down by swiftly moving currents of water which tend to carry away the lighter and finer material in suspension. Hence they represent the deposits of rapid rivers and estuarine currents. Also, when a sinking land surface passes under the sea and the edge of the latter advances, a beach formation sweeps over the land as the initial stage to later deposits. The waves throw the coarser material, the gravel or shingle, toward the upper part of the beach and as the latter sweeps inland a conglomerate is thus the first deposit laid down on the new sea bottom. Thus it is general to find a conglomerate or coarse sandstone as the first member of a new series of stratified rocks, resting upon an unconformable lower series, and in thus marking divisions of geologic time they may be of great importance. They are quite common rocks and are everywhere distributed in the sedimentary formations.

In the older, and especially in strongly folded mountain regions where the strata have suffered great pressures and shearing, the pebbles of conglomerates are generally distorted and flattened into lenses, or drawn out into spindle-shaped forms. The process is generally accompanied by mineralogical changes which may be especially noticeable in the cement. This is the first stage in the conversion of these rocks into gneisses and schists through metamorphism, as described in the following chapter. On account of their coarse and irregular appearance and unhomogeneous character conglomerates have been little used for structural purposes, except in the roughest stone work, as in foundations, piers, etc. In some cases breccias, which are compact and capable of a good polish, have been cut as ornamental stones, as a reddish conglomerate breccia from South Dakota and a vari-colored limestone breccia from Japan. Since the discovery of the wonderful gold deposits in conglomerates in the Rand district, South Africa, these rocks have received much attention, as representing possible fossil placers in which, if the gold has been concentrated by natural processes, available sources of the precious metal might be expected.

SANDSTONE AND RELATED ROCKS.

Sandstone. Typical sandstones are composed of grains of quartz held together by some substance acting as a cement. The size of grain may vary from that of peas down to that of fine seeds; as they become finer the rocks pass into shales, just as on the other hand they graduate upward into conglomerates, and thus no sharp line can be drawn between the three kinds. While some sandstones are very pure, consisting of quartz grains alone, others contain intermingled particles of feldspar, garnet, iron ore, tourmaline, flakes of mica and fragments of other minerals. It can generally be observed with a lens that the grains tend to be spheroidal, and that the larger they are, the more perfect the rounding is apt to be. The general appearance of many sandstones, with respect to their granular texture, is much like that of loaf sugar. As described under quartzite, to which reference should be made, the fracture, in breaking sandstone, takes place chiefly in the cement, leaving the grains outstanding, and this gives the rock its sugary appearance and feeling.

Sandstones differ very much in regard to the cementing material which holds the grains together, and thus different varieties are produced. Sometimes it is deposited silica, sometimes a carbonate — commonly calcite, but on occasion dolomite or siderite, — sometimes extremely fine argillaceous material or clay, and at other times deposited oxides of iron, either reddish (hematite, turgite), or yellowish (limonite).

The colors are very variable, white to gray, buff to dark yellow, and brick-red to reddish brown and brown, are common; green, purple and black are rare. These colors depend largely on the nature of the cement; in the yellow, red and brown sandstones oxides of iron predominate, with the other, lighter colors, it is apt to be calcareous or argillaceous. In addition, the calcareous sandstones are readily detected by their effervescing when touched with acid, while the argillaceous ones give the characteristic odor of clay, when breathed upon. The green color is due to glauconite, or in some cases admixed chlorite. Some varieties appear to be almost devoid of a cement.

Sandstones are usually very porous rocks, and this appears to depend to a large extent upon the amount and character of the interstitial cement. Thus the ratio of the volume of pore space to that of the rock has been found to vary from 5 to almost 30 per cent, the latter being about the greatest amount theoretically possible in deposited sand grains.

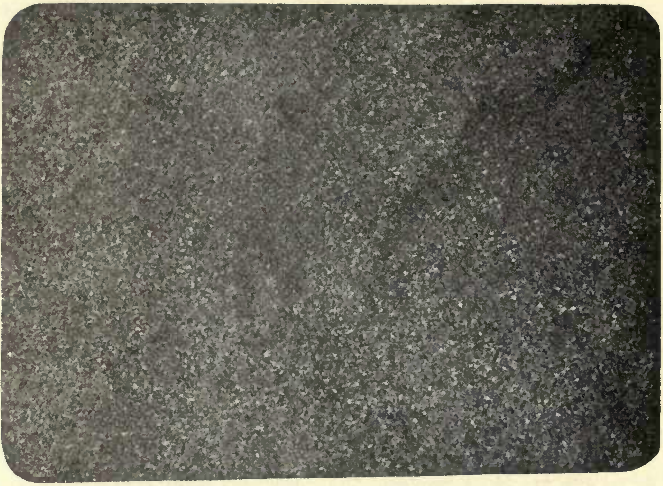
The same characters also condition to a large degree other physical properties and also explain their variations: thus the weight per cubic foot varies from 125–150 pounds, the crushing strength from 1500 to 15,000 pounds per square inch. The specific gravity is about 2.6 (2.5–2.7), with the rock pores filled with water, when weighed in it.

The chemical composition of sandstone varies considerably; the chief element is silica, but the proportions of the other elements depend on the nature of the associated minerals and cement. Some analyses of prominent sandstones used for building purposes are as follows:

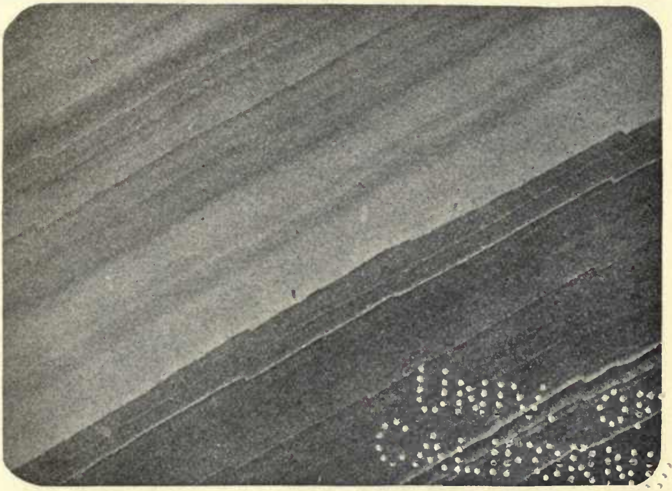
	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	K_2O	Na_2O	H_2O	CO_2, etc.	Total
I....	99.4	0.3		–	–	–	–	–	0.2	–	99.9
II...	86.6	8.4	1.6	–	–	trace	2.4	0.7	–	–	99.7
III..	92.9	3.8	trace	0.9	trace	0.3	0.6	0.3	1.2	–	100.0
IV ..	69.9	13.6	2.5	0.7	trace	3.1	3.3	5.4	1.0	–	99.5
V ...	87.1	3.9	1.3	–	1.1	2.7	1.3	0.8	0.5	1.4	100.1
VI ..	90.7	4.6	0.4	0.1	0.1	0.1	0.5	2.8	0.4	0.3	100.0

I, White, very pure Potsdam Sandstone, Ablemans, Sauk Co., Wisconsin; II, Lake Superior Brownstone, Houghton, Bayfield Co., Wisconsin; III, Sandstone, light gray, Berea, Ohio; IV, Brownstone, Triassic, Portland, Conn.; V, Sandstone, Triassic, near Liverpool, England; VI, Bunter sandstone, Heidelberg, Germany.

PLATE 33.



A. SANDSTONE, OF FINE GRAIN.



B. LAMINATED SANDSTONE, WITH SLIGHT FAULTS.

The presence of the alkalies points to that of feldspar (or mica) in the rock; in IV the amount of feldspar must be large, and such a rock is to be classed as an arkose rather than a sandstone.

The structure of sandstones is essentially that of the stratified rocks. They are sometimes thinly laminated and fissile, and sometimes very thick bedded and within the individual bed may show a very even texture and be practically free from any evidence of stratification. Sandstones such as the latter are valuable for structural purposes on account of their homogeneous character and capability for cleaving or working equally in all directions; they are often called *freestones.*

These rocks are frequently distinguished according to the character of the cement or admixed material as described above; thus there are *calcareous* sandstones, *argillaceous* sandstones, *ferrugineous* sandstones and *siliceous* sandstones. *Micaceous sandstones* contain considerable muscovite; the tabular flakes are parallel to the bedding and induce a more or less ready cleavage in the rock, giving it a fissile character; the cleavage faces are apt to be somewhat silvery in appearance from the mica films coating them. *Grit* is a term applied to coarse-grained sandstones whose particles are in general more or less sharply angular, and whose cementing material is, as a rule, quite siliceous. They have been considerably used for grindstones and millstones, hence the term " millstone grit." In siliceous sandstones it may happen that the deposited silica is precipitated upon the rounded or angular quartz grains in crystalline position, thus reconverting them outwardly into crystals; examination with the lens shows the crystal forms and faces of the little regenerated quartzes; these are known as *crystal sandstones.*

Green sandstone is a variety full of grains of glauconite which impart a general greenish color to the rock. Sometimes these rocks are very friable, indeed scarcely coherent, as in the Cretaceous formations of the Atlantic border, especially in New Jersey. They are then called *greensand* or, inappropriately, *greensand-marl.* They are apt to contain, in addition to the sand and glauconite, iron oxides and fossil shells, either whole or fragmentary. These deposits have been considerably used as fertilizers. Analyses of typical greensands from New Jersey are as follows:

SiO_2	P_2O_5	SO_3	Al_2O_3	$\underbrace{Fe_2O_3FeO}$	MgO	CaO	K_2O	H_2O	Total
34.5	1.2	1.3	6.0	31.5	2.2	2.5	1.5	18.8	99.5
51.2	0.2	0.4	8.2	23.1	2.0	0.5	7.1	6.7	99.4

Arkose. This is a special variety of sandstone in which a notable quantity of feldspar grains is mingled with those of quartz. Often there is considerable mica present and, if the material is firmly cemented, the rock to a casual glance may bear no small resemblance to a granite. The particles are generally sharply angular, and the feldspar is apt to be soft and more or less changed to kaolin. Under a lens the irregular, clastic, angular shape of the particles readily distinguishes it from a granite. The mineral composition and the shape of the grains show that the material has been derived from quickly disintegrating granite and has suffered but a very short transport before being deposited. Arkoses often grade into conglomerates and breccias by increasing size of some of the particles. They occur in all of the different geological formations. The red-brown Triassic sandstones of New England are in large part arkose and conglomerate or breccia.

Graywacké. These are sandstone-like rocks of a prevailing gray color, sometimes brown to blackish, which, in addition to the quartz and feldspar of an arkose, contain rounded or angular bits of other rocks, such as fragments of shale, slate, quartzite, granite, felsite, basalt, etc., or of varied minerals, hornblende, garnet, tourmaline, etc. They are in reality fine-grained conglomerates and readily pass into them by increase in size of some of the component particles. The amount of cement, as in sandstones, is usually small and it is generally argillaceous, but sometimes siliceous or calcareous. Such rocks, when fine grained and compact and largely composed of feldspathic material, may be difficult in the hand specimen to distinguish from some felsites, but close examination with a good lens will generally show their nonhomogeneous character. The name has been rather loosely used and has never had the vogue in America that it has in Europe.

Uses of Sandstone. As is well known, sandstone is everywhere used for constructional purposes. The ease with which it is worked, and the large size of the blocks which may be quarried, make it particularly valuable for this purpose. Thus in the United States a very considerable portion of the buildings of the eastern cities are wholly or in part of the red-brown sandstone, generally called "brownstone," of the Triassic areas of the Atlantic border, while for instance in Great Britain the city of Edinburgh is largely built of the Carboniferous sandstones of that region. On account of the insoluble nature of the iron oxide forming their cement, the red and brown sandstones in moist climates retain much better the details of fine cutting and carving for architectural effects, than do the lighter colored gray or buff stones. The latter are liable to have a calcareous cement, which dissolves under the action of atmospheric agencies and water, allowing the stone to crumble, and thus in the course of years the fine details of carving are spoiled. Many examples of this may be seen in the older cities where expensive and beautiful buildings have been much injured. If possible, in building, a sandstone should always be laid upon the quarry bed as it is then much less liable to flake or spall.

Sandstones are of such wide and general distribution in all parts of the world where stratified rocks are found, that it is unnecessary to give any detailed account of their occurrence.

SHALE AND RELATED ROCKS.

Shale is the name given to compacted muds and clays which possess a more or less thinly laminated, or fissile structure. The parting is parallel to the bedding, and is the result of natural stratification. When such rocks have been subjected to folding and pressure, they assume a slaty cleavage which has nothing to do with stratification; they are then slates or phyllites and are described among the metamorphic rocks. This distinction, that rocks showing slaty cleavage are not shales, should be clearly noted, as the two are often confused.

Shales are, in general, too fine grained for the component particles to be determined with the eye, or even with the lens. By microscopical and chemical analysis they are known to be formed mostly of kaolin and related substances, with which may be associated much white mica, but these are often accompanied by tiny fragments of quartz and other minerals. As the amount of quartz increases, and also the size of grain, the shales pass over into sandstones, and such intermediate rocks represent deposited silts. There are also all transitions between clays and shales, depending on the relative firmness and fissility of the mass.

Clay when dry is a fine, earthy, lusterless mass, giving a characteristic odor when breathed upon. It clings to the tongue, and when strongly rubbed to a powder between the fingers, it finally produces a soft, greasy, lubricated feeling, usually thus differing from loess, adobe, and similar appearing deposits. It absorbs water eagerly and becomes plastic. When pure it is white, but it is generally colored red or yellow by iron oxides, forming the red and yellow *ochers*, or gray, blue or black by organic substance. The colors are sometimes evenly distributed, and sometimes irregularly blotched, through the mass.

Shales are apt to be soft, cut more or less readily with the knife, and are brittle and crumbly, so that taken in connection with the fissility, it is often difficult to prepare hand specimens of them. Like clays they exhibit a great variety of colors, white to buff or yellow, red to brown, purple, greenish and gray to black, and from the same causes. Different shades of gray are perhaps the most common. They often contain various accessory mineral substances, such as carbonates, gypsum, rock-salt, pyrite, etc. Some of these are frequently seen in the form of concretions, which may attain large size, up to several feet in diameter.

The chemical composition is somewhat variable, depending on the relative proportions of clay and other minerals. The following analyses will serve to show the general chemical character.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
55.0	21.0	5.0	1.5	2.3	1.6	0.8	3.2	8.1	1.9	100.4
60.6	16.4	4.9	—	1.4	1.6	0.9	3.0	9.7	1.5	100.0
61.2	15.6	1.4	3.0	4.2	3.4	0.4	6.7	2.7	1.1	99.7
53.6	17.6	4.1	3.7	5.2	2.3	2.5	2.2	8.5	0.2	99.9

I, Cambrian Shale, Coosa Valley, Cherokee Co., Alabama; II, Cretaceous Shale, near Pueblo, Colorado; III, Devonian Shale, Morenci district, Arizona; IV, Cretaceous Shale, Mount Diablo. California.

XyO = Carbonaceous matter, CO_2, and small amounts of other substances.

There are many varieties of shales, depending chiefly on the presence of accessory materials. Thus there may be a large amount of organic matter, mostly carbon, present, and such are called *carbonaceous shales.* They are black in color, and by increase of carbon, grade into coaly shales, shaly coals and so on into coal. They are a very common type, and are found associated with coal and also independently of it, sometimes covering wide areas and of great thickness. From the nature of the organic matter they are sometimes called *bituminous shales.* It is probable that the total amount of carbon in the shales far exceeds that existing in coal beds.

In other varieties of shales large amounts of carbonates, especially carbonate of lime, are present, and these are known as *calcareous shales.* By increase of this substance they pass into shaly limestones. They are apt to be associated with limestones and these calcareous varieties are detected by their ready effervescence with acids. Or the carbonate present may be chiefly carbonate of iron and thus produce transition forms between shales and clay ironstone previously described. The connection between clays, shales and marls has been mentioned on a previous page. *Alum shale* is a variety full of pyrite, or of sulphates resulting from its alteration; it has been used for the manufacture of alum.

Uses of Clay and Shale. The use of clay in the making of bricks, tiles, pottery, etc., is too well known to need further comment. Shale has no value for structural purposes, but in recent years, along with clay, it has become of value and is used in many places as a material for the manufacture of Portland cement, when mixed with the proper proportion of limestone and burned. A pure, clean shale or clay of the general composition shown in analysis No. II, given above, is one best adapted for this purpose, when combined with a non-magnesian limestone.

Clays and shales are such common rocks in all parts of the world, where the unmetamorphosed stratified formations are found, that their occurrence needs no special description.

Surficial Deposits.

This small group of geologic materials is of somewhat diverse origin, and they are here included under this heading largely as a matter of convenience. They would include æolian deposits, or those made by the wind, and those formed by the disintegration and decay of previously existent rocks. They are appended here to the stratified rocks, because they are in general closely connected with them, and in many cases pass insensibly into them. Many indeed, which might be classed here wholly or in part, have already been described elsewhere because of their close connection with other rocks. Thus *volcanic tuffs* and *breccias* have been described under igneous rocks; *clays* under shale, *marl* under carbonate rocks, *sands* in Chapter VIII, etc. Most of these substances, under the ordinary usage of the word, would not be considered rocks at all, and their treatment entails matters of geological interest rather than such as enter into a work of this character. This applies to such things, for instance, as soils, talus heapings, morainal deposits from glaciers, etc. Their description and mode of origin should be sought in the handbooks on geology, or in special manuals. Only a few of them, which from their widespread occurrence and great importance as geological formations are of particular interest, are here included.

Loess. This is a deposit of a pale to buff yellow color, running into brown, of an exceedingly fine grain; friable, with scarcely the consistency of ordinary chalk when coherent, and passing into looser forms, and of a rather harsh feeling when rubbed between the fingers. It is of a remarkably homogeneous appearance, and commonly shows no signs of stratification, though this is sometimes clearly seen. It has been found to consist chiefly of angular grains of quartz, mixed with considerable amounts of clay-like substances, tiny specks of other minerals, and a calcareous cement, the amount of carbonate of lime rising in some cases to 30 per cent. This latter produces an effervescence in acid which quickly ends. The analysis of a loess from Kansas City, Missouri, may be quoted to show the general chemical composition.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	CO_2	XyO	Total
74.5	12.3	3.3	0.1	1.1	1.7	1.4	1.8	2.7	0.5	0.4	= 99.8

XyO = minute quantities of P_2O_5, TiO_2, SO_3 MnO and C.

Loess occurs in widespread areas in the valley of the Mississippi, in the states of Ohio, Indiana, Illinois, Iowa, Kansas, Nebraska, Arkansas, Missouri, Tennessee, Kentucky, Alabama, Louisiana, Mississippi, and Oklahoma. It is found also in Europe in various places, especially in the valleys of the Rhine and its tributaries, lying in isolated patches on the upper hill and mountain slopes and in the same way in the Carpathians. It covers an enormous area in northern central China with thicknesses attaining 1500–2000 feet, and the yellow color which it imparts to the Hoang-ho (Yellow River), and eventually to the Yellow Sea, into which the former discharges, gives to these their names.

It is now generally accepted that the loess is an æolian, that is, a wind blown deposit of dust which has accumulated through long periods of time. This is shown by its lack of stratification, the spread out manner in which it lies upon the surface, filling former inequalities, the remains of land shells which are found in it, and by the small, vertical tubes running through it caused by the roots and stems of former vegetation. In places, however, where it has been washed down into former lakes, ponds and streams, it becomes stratified. In America and Europe, the material of the loess is supposed to represent the finely ground rock powder of the glacial ice sheet.

A characteristic feature is the common occurrence of concretions of carbonate of lime and of oxide of iron. They often assume the odd shapes seen in the flint nodules of chalk. The perpendicular tubules give to the loess a vertical cleavage, which produces along river banks bold bluffs.

Adobe. This name is applied to a very fine-grained, coherent, yet friable material which covers wide areas in the semi-arid and arid regions of western North America, especially in the southwestern states and in Mexico. It resembles loess in many ways, has usually the harsh feeling, when rubbed between the fingers, and is of a yellowish, yellow-brown, gray-brown or chocolate-brown color. Its use in the form of sun-dried brick for building is well-known. It is the result of the finer detritus of rock decay on the higher slopes of hills and mountains accumulated on the lower slopes, plains, valleys and basins, in part by rain wash, and in part by the action of the wind in moving it as dust. It forms a valuable soil when irrigated and brought under cultivation.

Laterite. This is a red soil or deposit found in tropical regions and is the result of the sub-ærial decay of many rocks, especially of granite. In the process the rocks lose their alkalies and alkali-earths more or less completely, and there remains a reddish, cellular mass, consisting of quartz sand mixed with clay-like substance (chiefly hydrargillite, $Al(OH)_3$) with iron oxides which give the color. When dried it may become very hard and rock-like. It frequently contains concretions of the iron oxides.

Loam. The common arable soils of the greater part of the world are comprised under this heading. Loam consists of a mixture of sand and clay, colored yellow, brown, or reddish by iron oxides, or dark to black from organic matter. The sandy particles are chiefly quartz, often mingled with fragments of other minerals. On rubbing between the fingers, it first feels harsh from the gritty sand particles; if the rubbing is continued and these are allowed to drop out, the greasy smooth feeling of the clay is finally perceived. The proportion of organic matter varies very greatly; the black soils of India and Russia are very rich in it.

CHAPTER X.

THE ORIGIN AND CLASSIFICATION OF METAMORPHIC ROCKS.

Introductory. The metamorphic rocks are those which, originally sedimentary or igneous, have been changed either in mineral composition or in texture, or in both, so that their primary characters have been altered, or even entirely effaced. Here constantly, as elsewhere in geology, gradations exist, and no definite line can be drawn on the one hand between the sedimentary rocks and their metamorphic products, or between the igneous rocks and the metamorphic ones formed from them, on the other. Thus loose chalks pass into limestones, and these into crystalline marbles, just as dolerites merge into greenstones, and so on into hornblende schists, without any sharp line of demarkation. But there comes a point in the change of each original rock, either of composition or of texture and usually of both, where its characters and relations to other rocks have become so individual that, for practical purposes, it is best regarded as a distinct kind of rock. Where this line shall be drawn must depend upon the experience and judgment of the observer; in this work only those cases are treated where the change has been so definite and pronounced as to produce typical metamorphic rocks.

Rocks for the most part are composed of minerals, and minerals for the most part are definite chemical combinations, which are only, as a rule, permanent under stable conditions. If the minerals are submitted to new conditions, quite different from those under which they were formed, with new chemical and physical factors operating upon them, they will tend to change into other minerals, that is, to turn into new chemical combinations, which will be the most stable under the new conditions. A familiar example is the decay of the feldspar of igneous rocks, and its change into clay and other substances through the action of water and carbon dioxide, as treated under granite. The change in conditions may be so slight that some rock minerals may be able to resist them indefinitely, while others less stable may succumb. Thus igneous rocks, formed by the cooling and crystallization of molten magmas, may remain in the depths for millions of years, and on coming to the surface through erosion and denudation, may be found entirely unchanged, or with only one or two of the constituent minerals altered. At the surface they are at once subjected to new conditions, to the combined effects of changes of temperature, to moisture, the various gases of the atmosphere, the products of organic life, etc., and they commence to break up and to form into new compounds. Then their ultimate conversion is only a question of time. The same is true of the sedimentary rocks, only in lesser degree. They are formed of mineral particles, deposited in water and, usually, cemented by pressure and deposits from solution. While they remain deeply buried and under fairly stable conditions, they are unchanged; when they are exposed to the atmosphere they also tend to change and decay, especially in those minerals that are susceptible.

All these changes which occur upon the surface are strictly to be classed as metamorphic ones, and the products, in a geologic sense, are metamorphic rocks. But for practical purposes all these materials formed by the action of weathering and by the decay of rocks on or near the surface, such as the soils, are not here included. They have been previously mentioned under the foregoing rock types, so far as seems desirable for the object of this work, and only those rocks are treated as metamorphic which, while buried at depth below the surface, have suffered, through the action of certain agencies to be presently described, changes, which have practically converted them into new kinds of rocks.

Metamorphic Agencies. The chief metamorphic agencies are mechanical movements of the earth's crust and pressure, the chemical action of liquids and gases, and the effect of heat. We may simplify these into the effects of movement, water solutions, and heat, and all three of these are required to produce complete metamorphism in rocks, though not necessarily all to the same extent, since sometimes one factor is more predominant, and sometimes another. Thus in the metamorphism which has been already described as contact metamorphism, induced by the intrusion of a body of magma, the effect of heat is the most important, that of gases and liquids less so, while the effect of movements of the crust, or pressure, is negligible. The rocks produced, however, are actually metamorphic, but for practical reasons they have been given separate consideration, and are not included among these under treatment. We will consider the different agencies separately.

Movement and Pressure. Pure simple downward pressure, to the amount exerted in the upper part of the earth's outer crust, appears to have little metamorphic effect. It tends without doubt to consolidate the material of sediments by bringing the grains closer together, but many instances may be cited of sediments, buried under great thicknesses of deposits for geologic ages, which on being raised and exposed by erosion without disturbance, such as folding, are found to be practically in unchanged condition.

On the other hand, as commonly supposed, through the gradual contraction of the earth, the outer crust is under compression, and this finds relief from time to time by buckling or wrinkling up of the outer shell into mountain ranges. This compressive force, thus acting with lateral thrust, is therefore spoken of as orogenic, i.e., mountain forming. By it whole masses of strata with possibly included igneous rocks — intrusive, extrusive and fragmental volcanic — are folded, crushed, and mashed together in the most involved and intricate manner. Not only are the rocks then subjected to vast pressure, but they are also subjected to enormous shearing stresses, which tend to produce forced differential movements among the rock particles. It is particularly this latter effect which is of great potency in producing metamorphism. Its effects may often be seen megascopically by the manner in which large crystals, included pebbles, or fossils are flattened and elongated, or broken into fragments which are drawn out into thin, lenticular masses in the direction of shear. The microscope shows that even minute crystals are broken, and their optical properties affected, as the result of the strain. It is possible indeed, for this agency working alone to produce rocks having the characteristic outward metamorphic texture, without any change in their original mineral composition, but in combination with heat and water, it is of the highest importance in inducing chemical changes, and the production of new minerals. It is indeed a noticeable fact that so long as the rocks retain their original position, they are unaltered, but as we commence to find them disturbed by orogenic forces, they begin to show signs of metamorphism, and in proportion to the degree to which they have been folded up, mashed, and sheared, they become more and more metamorphosed.

Heat. The effect of heat as a metamorphic agent is very powerful, as is so well shown in local or contact metamorphism. It increases very greatly the solvent action of solutions; it tends in many cases to break up existing chemical compounds which form minerals, and to promote new chemical arrangements. The heat needed for metamorphism may come from the interior of the earth, which increases greatly with the depth; it may be supplied in part by the transformation of energy resulting from the movements, the folding and crushing of the rock masses.

and in part it may result from intrusions of molten magma, which are very liable to rise and invade the rock masses as they are uplifted and folded.

Liquids and Gases. The chief of these is of course water, which under heat and pressure becomes a powerful chemical agency. It acts as a solvent, and promotes recrystallization, and taking part in the chemical composition of some of the minerals, such for example as micas and epidote, it is a substance necessary to their formation. It is, without doubt, aided also in its action by substances it may carry in solution, such as alkalies, and by volatile emanations coming from magmatic intrusions, like boric acid, fluorine, etc., as already explained under contact metamorphism. It is this which explains the presence in metamorphic rocks of such minerals as tourmaline, chondrodite, and vesuvianite, which are characteristic of pneumatolytic contacts, and of micas, hornblendes and other minerals which contain fluorine.

Effect of Depth. The outer crust of the earth has been divided by geologists into different zones, according to the various geological processes at work. In the outermost one, down to the level at which ground water stands, the rocks are full of fractures, and are exposed to atmospheric agencies — moisture, carbon dioxide, oxygen, etc. In this the rocks tend to decay, to be converted into carbonates and hydroxides, and to form soils. It is called the *belt of weathering*, and is the one of rock destruction. Below this lies another, in which the rocks are also full of fractures and cavities filled with water. Its upper level is that of ground water; below, it reaches to the point where the pressure of the superincumbent masses and the contraction of the crust becomes so great that all fractures and openings are closed up, since the stress is so much greater than the strength of the rocks, that they crush under it, and are to be regarded as being in a relatively plastic state. In this zone the chemical action of water is most important, aided by the substances it may carry in solution. The tendency is to change the minerals to hydrates, and to a lesser amount to carbonates; thus olivine, an anhydrous silicate, becomes converted into the hydrous silicate, serpentine. Substances are taken into solution and, reinforced by those leached out from the belt above and carried down, are deposited in the pores and fissures of the rocks; hence it is called by Professor Van Hise the *belt of cementation,* because the rock-grains are thus cemented together.

Below this lies the zone where, as stated above, the pressure becomes so great that all openings are closed up, and the rocks may be regarded as in a plastic condition. Its upper level is variable and depends on geological conditions; in times of quiet it may be as deep as six miles below the surface; in times of mountain making, it may rise much higher than this. Of what may be its lower level, we know nothing. In this, the chief agencies are the enormous pressure and the increasing heat of the earth; the rôle played by liquids and volatile substances is of less importance; the tendency is for them to be gotten rid of, to be squeezed out. The chief work done in this zone is molecular rearrangement, in which less stable mineral compounds are broken up, and new ones of higher specific gravity and smaller volume, through condensation, are formed. Carbonates are converted into silicates and the carbon dioxide expelled; hydrated minerals have their water driven out and new minerals, with less or no water, are formed. This zone of rock flowage, in contrast to the zone of fracture above it, has been called the zone of anamorphism by Professor Van Hise. We may term it the zone of *constructive metamorphism.*

It is chiefly in the lower part of the belt of cementation (zone of fracture), and the upper part of the zone of rock flowage, that the greater part of the work of metamorphism, in the production of the metamorphic rocks as we see them, is done. In the upper zone, the results are chiefly those produced by dynamic shearing, and the imposing upon the rocks of characteristic textures. Chemical work may be done and new minerals produced, but it is possible for new textures to be formed without change in mineral composition. In the lower zone, the work done is largely chemical, new and more stable mineral combinations being formed; and here also characteristic textures are produced.

Minerals of Metamorphic Rocks. Just as certain minerals, of which nephelite and sodalite might be mentioned as examples, are characteristic of igneous rocks, so other minerals are peculiar to the metamorphic ones, such as *cyanite, zoisite, staurolite* and *talc.* Other minerals are found in both groups alike, such as *quartz, feldspar, hornblende, pyroxene, garnet* and *mica.* It should be remembered, however, that the names just mentioned are really names of families, under which quite a variety of individual mineral species may be grouped, on account of certain common properties, such as crystal form. Thus in the hornblende group, arfvedsonite is found only in igneous rocks; *tremolite* and *uralite* occur practically only in metamorphic ones; *common hornblende* occurs in both. Of the pyroxenes, the normal home of augite is in igneous rocks, of *wollastonite,* a pyroxene-like mineral of the composition $CaSiO_3$, in the metamorphic ones; *common pyroxene* in both. Of the micas, *paragonite* has been found only in metamorphic schists, *biotite* and *muscovite* are present in both groups of rocks, but muscovite is relatively rare in fresh, normal, igneous ones. In the garnet group, pyrope, the magnesia-alumina garnet, is formed only in igneous rocks very rich in magnesia and low in silica, such as the peridotites; it occurs in them, or in the serpentines formed from them, while *grossularite,* the lime-alumina garnet, has its characteristic home in metamorphic limestones; *almandite* and *common garnet* are found both in igneous and metamorphic rocks. In the following list are given the minerals which may occur in metamorphic rocks; the first column contains those of wide distribution, and of prime importance, as chief components; the second column, those of lesser importance, which occur either as prominent accessory minerals, or locally developed as chief components; the third, occasional minerals, which may be at times megascopically developed. But this is true only in a general way, and over emphasis must not be laid on these divisions.

I	II	III
Quartz	Garnets	Graphite
Feldspars	Staurolite	Tourmaline
Biotite	Epidote	Chrondrodite
Muscovite	Zoisite	Vesuvianite
Hornblendes	Cyanite	Hematite
Calcite	Pyroxenes	
Dolomite	Magnetite	
Chlorite	Talc	
Serpentine		

Of these minerals, chlorite, serpentine, and talc are specially characteristic of the upper zone, while cyanite, staurolite, and some of the others are formed in the lower zone. Some minerals, like quartz, and some members of the groups may be formed in either zone, or be persistent components of the original rocks.

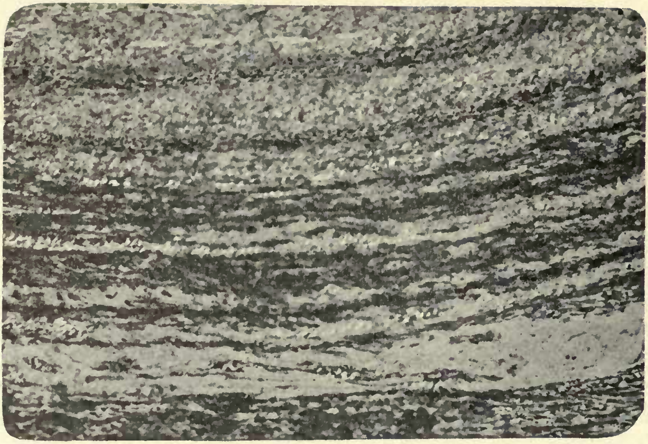
Texture of Metamorphic Rocks. The metamorphic rocks resemble the greater part of the igneous ones, in that they possess a highly crystalline character, so much so that they are frequently referred to as the *crystalline schists*. On the other hand, they resemble the stratified ones in possessing a parallel structure which may closely resemble stratification. Thus they show analogies to both of the other great rock groups. This parallel structure expresses itself to a greater or lesser degree by a foliated, laminated, or, as it is frequently termed, a *schistose* texture, one in virtue of which the rock tends to split or cleave more or less perfectly in the direction of a certain plane passing through it. This direction of cleavage is called the *chief fracture*, and the break of the rock at right angles to it is termed the *cross fracture*. Highly crystalline rocks exhibiting this texture are called gneisses or schists, according to their mineral composition, as described later. While it is the characteristic texture for the metamorphic rocks, there are a few, such as serpentine, marble and quartzite, that for certain reasons to be explained, may not show any trace of it, and yet are true metamorphic rocks.

Observation of the gneisses and schists shows that this texture is due to arrangements of unlike mineral grains in layers, or very flat lenses, or to a parallel arrangement of minerals having prismatic or tabular forms, such as hornblende or mica, or to a mixture of both. It is a result of the orogenic forces, the shearing and pressures to which the original rocks have been subjected, and it makes no difference whether these were igneous or sedimentary, this texture may be imposed upon both alike under proper conditions. The superficial resemblance, which the gneisses and schists bear to stratified rocks in their parallel laminated character, for a long time led geologists to think that the former must have been derived wholly from the latter, and the general recognition that they contain former igneous ones as well has come only in the last twenty-five years through petrographic and chemical studies. From the fact that in places stratified rocks could be traced into metamorphic ones and the latter into igneous ones, it was even assumed that the igneous rocks were in part derived from sediments by extreme metamorphism. Such cases merely represent instances where both have been metamorphosed in common, with a remnant at either end which is not metamorphosed, and whose original characters may therefore be recognized. In the light of our present knowledge we should be no more justified in tracing out such a deduction, than we would in reversing it, and deriving the stratified rocks from the igneous ones by metamorphic processes!

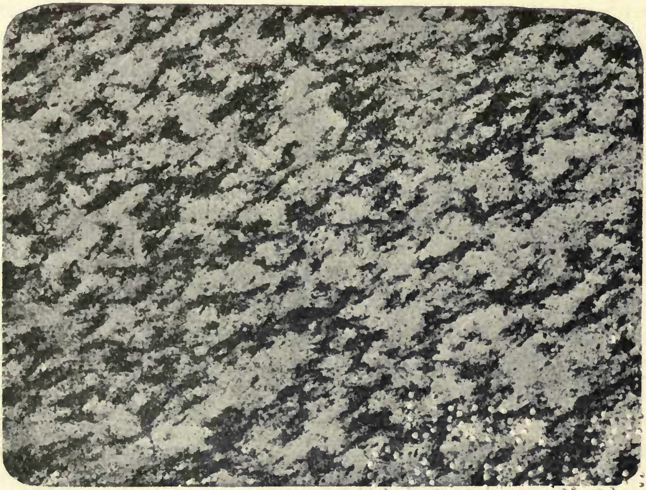
Varieties of Texture. Three chief varieties of the schistose texture may be recognized, (1) the *banded*, in which unlike mineral layers are in parallel bands, as shown in Fig. A, Plate 34. This resembles stratification, but may be induced in igneous masses as the result of shear. (2) the *lenticular*, or *foliated*, in which some of the components are collected into thinner or thicker lenses, around which the other minerals tend to be wrapped or wound, as shown in Fig. B, Plate 34, which shows a view of the cross fracture. The surface of chief fracture in this case is apt to be more or less lumpy, and not to show well the minerals of the lenses. Both this and the foregoing variety vary greatly from coarse to fine. (3) The *slaty* texture is one in which the mineral grains are extremely small, usually too small to be seen with the eye, and often even with the lens; the rocks appear dense, but they have the capacity of splitting into thin slabs, as seen in roofing slates. The cause of this is discussed under the description of slates.

Metamorphic rocks frequently contain large and well-developed crystals of minerals, which have formed as a result of the processes to which the rocks have been subjected. These may be very much greater in size than the average grain of the rock, and this contrast, together with the perfection of their crystal form, produces a strong analogy to the porphyritic texture of igneous rocks. They are not true porphyries, however, not only because the texture is not of igneous origin, but also because these large crystals are not of an older generation, but are actually of later formation than the minerals of the apparent groundmass in which they lie. It is therefore termed the *pseudo-porphyritic texture.* That these minerals or pseudo-phenocrysts are of later formation is shown by the fact that they frequently contain as inclusions the other rock minerals, and sometimes the inclusions, such as bits of quartz, graphite, etc., pass through the large crystal in the lines of original stratification, and out beyond it. Moreover, it may be frequently noticed that where these pseudo-phenocrysts are not equidimensional, but elongated, they may lie in the rock pointing in all directions; their longer axes do not necessarily lie in the direction of schistosity, like those older minerals, which have been arranged by the pressure and shearing. Having grown *in* the zone of pressure, they are not oriented by it, unless subsequent and later movement and shearing should take place after their for-

PLATE 34.



A. BANDED GNEISS.



B. LENTICULAR OR FOLIATED GNEISS.
(Maryland Geological Survey.)

mation. The space in the rock in which movement of material goes on to produce these larger crystals is clearly shown in Plate 35, which is a photograph of a garnet in gneiss. Around the garnet is a zone of feldspar, from which all the ferromagnesian minerals, visible beyond it, have disappeared, having been used up in its formation.

The crystals described above should not be confused with larger crystals or crystal masses in the rock, which may also give it a porphyritic, appearance, but which are really remains of former structures. Such may be former phenocrysts of some porphyritic, igneous rock, or large grains from some former coarse-granular igneous rock, or a pebble from a conglomerate. They are apt to form ovoïd masses, and they are then really a pronounced case of the lenticular texture, which is sometimes termed, following the German name, *augen* (eye) *texture*.

Relation to Previous Textures, etc. In proportion to the degree of metamorphism which rocks have suffered do we find that the characteristic textures described above have been imposed upon them. But not infrequently, as though looking through the veil which metamorphism has cast over them, we can see back of these features remains of original textures and structures which are characteristic of igneous and sedimentary rocks. Thus, as indicated above, we may see that the original texture was that of a porphyry, or we may find remnants of the spherulites, lithophysae, and flow lines of some felsite lava,or of the amygdules of some basaltic one; on the other hand, ovoid masses of different mineral composition may indicate a former conglomerate, or parallel layers, differing in general mineral and chemical composition, may show former stratified material. Such indications may be very useful in ascertaining the former origin of a metamorphic rock, and in some cases may positively identify it, but deductions from this source should always be made tentatively, and used with great caution, for there are many confusing appearances of this kind which may lead to serious error, unless they are checked by microscopic examination and chemical analyses.

Chemical Composition. The chemical composition of the metamorphic rocks is extremely variable, and it is evident that this must be the case, when one considers the heterogeneous materials from which they may be derived. If we take them together, as a class of rocks, the composition, therefore, cannot have the significance which it plays in the igneous ones, in showing their mutual relations. It may, however, be of great importance as an aid in helping to determine their origin. Thus, in examining the chemical analysis of a metamorphic rock, we may be able to say that it is similar to those of known igneous rocks and it may therefore have been originally of igneous nature, and on the other hand the analysis may show definitely that it could not have been any igneous rock, and consequently it must have been of sedimentary origin.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I...	75.7	13.2	—	1.8	0.4	0.6	2.1	4.7	1.0	—	99.5
II..	50.3	14.1	7.0	5.3	7.2	8.1	4.0	2.3	1.6	—	99.9
III.	74.7	8.9	9.6	—	1.9	1.1	0.4	1.0	1.1	0.5	99.2

I, Gneiss, near Freiberg, Saxony; II, Hornblende Schist (amphibolite) Vestana, Sweden; III, Gneiss, near Rawdon, Quebec.

Thus, in the analyses given above, that of No. 1 might well be of an ordinary granite, as may be seen by reference to those given under granite; it might also, however, be that of an arkose derived from such a granite. No. II has the composition of a gabbro; it might have been such a rock originally, or a dolerite, or basalt; it does not suggest any ordinary sedimentary rock. No. III on the other hand has no analogy among igneous rocks; the alkalies and alumina are too low for the silica and the ferric oxide too high; it must be of sedimentary origin and suggests an impure, ferruginous sandstone.

It is inferred, of course, that while movement among the molecules within limited distances has occurred, whereby exchanges among the oxides are produced, involving recrystallization and the formation of new mineral compounds, the chemical composition of a rock mass as a whole has remained unaltered. That this is so, is shown by the fact, that in innumerable occurrences stratified rocks, although utterly changed in mineral composition from their former state, still retain the spacing and relative volume relations of the strata which they originally had. Thus one band of strata, perhaps only a fraction of an inch in thickness, is sharply marked off by its grain, minerals, and texture from those above and below it. There has been no melting and no formal transfusion of substance, consequently the changes which have occurred are, so to speak, inward, those which lie within the range of molecular attraction. To this general statement that there is no change in mass composition in metamorphism, there is one exception, and that is, that volatile substances, liquids and gases, may be driven out and, conversely, new ones may enter and pass into mineral combinations, as previously explained under the action of liquids and gases as agents. This is most strikingly seen, perhaps, in the metamorphism of impure limestones, as described in the section dealing with marble, and is thoroughly analogous to what has already been stated under contact metamorphism.

Injection of Gneisses and Schists. It has been previously mentioned that part of the heat of metamorphism, and of the liquids and gases involved in the production of minerals, is supplied by intrusions of igneous magma, which are particularly liable to rise and invade those areas where crustal movements are starting metamorphic agencies at work. In such areas, of course, the effect of contact merges into that of general metamorphism and no definite line can be drawn between them. Indeed the earlier formed intrusions may themselves become more or less metamorphosed, or have metamorphic textures imposed upon them by repetitions of the processes, and this may happen while they are in a solid, or yet partly plastic, condition. There is, however, another function which these magmas, rising under great pressure into rocks already schistose and foliated, may perform; they may squeeze themselves in thin veins, sheets, and lenticles into the schists surrounding them, so that these rocks may become partly igneous, partly metamorphic, in composition. And, as previously explained under contact metamorphism and pegmatite dikes, these effects may be greatly aided by liquid and gaseous emanations from the magma masses. This process has been termed the *injection* of schists by magmatic material and, although as it has been doubted by some geologists, just as it has been given entirely too general an application by others, it has undoubtedly occurred in many places. By it we are enabled to understand the veins, stringers, and lenses of granite penetrating the schists in the neighborhood of larger granite intrusions in many places, which would be otherwise incomprehensible. In this connection also, it should be remembered that the intrusive effects in the lower zone of rock flowage may be expected to be quite different from those in the upper zone of rock fracture.

Occurrence and Age. The metamorphic rocks have a wide distribution over the earth's surface, and in many places they occupy great areas, over which they are the only ones exposed. There is good reason also for believing that they form the basement upon which all the later unmetamorphosed, sedimentary rocks rest. The reason for this is, that wherever these later strata are sufficiently eroded away, this metamorphic basement has come to light. The only exception to this general distribution over the continental areas is in those places where later intrusions of igneous magmas have come up through them and are now exposed as bathyliths, stocks, dikes, etc. But these constitute but a subordinate part of the total area. It is their extension over such wide areas which has led to the processes, that have produced them, being called *regional metamorphism,* in contrast to the forming of the small zones around intrusive igneous masses, which is therefore termed *local metamorphism.* There is no difference in principle, however, between these two, only in the relative intensity with which the varied agents have operated. The metamorphic rocks are found also in folded mountain ranges, of which they form the interior core, and which subsequent erosion brings to light. In proportion to the intricacy of the folding and mashing of the strata, so is the degree of metamorphism increased. This is so well established, that when we find areas where the rocks are intricately folded and completely metamorphic, but not of any great elevation, we assume that such an elevation formerly existed, but has been eroded away, or in general that metamorphic rocks can only become exposed at the surface through erosive processes.

It is these facts that led to the view, formerly held, that metamorphic rocks must, geologically speaking, be of very great age. This is, however, by no means necessarily the case. For, on the one hand, we find unmodified sands of Cambrian age in eastern Russia, and unaltered beds of Ordovician age in the upper Mississippi valley, which have not been changed from their original position, while on the other, strongly folded strata of Tertiary age in the Coast Range, in the Alps, and in other mountains, are in places, profoundly metamorphosed. Rocks that are metamorphic are likely to be old, but not necessarily so, just as a battle-scarred soldier is likely to be a veteran, rather than a recent recruit. It merely depends on whether they have been subjected to metamorphic processes or not, and the older they are, the more likely they are to have suffered from them. Time, however, is one of the great factors in metamorphism, and even in the recent strata which have been changed, the time involved, from our standpoint, is very long.

Classification of Metamorphic Rocks. It would be natural to classify the metamorphic rocks according to the origin of their material, and to separate those of igneous from those of sedimentary formation. In some cases this may be done. Thus it is clear that marble is not of igneous origin, but when we attempt to carry this principle through, it quickly becomes impracticable, especially if we can use only megascopic means of determination.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O, etc.	Total
69.9	13.1	2.5	0.7	trace	3.1	5.4	3.3	1.0	99.0
69.9	14.9	1.8	0.6	0.6	1.5	5.3	3.9	1.3	99.8

Thus in the two analyses given above, the upper one is that of the Portland sandstone of Connecticut, a fine-grained arkose full of feldspar, the lower one that of an intrusive granite porphyry from the Crazy Mountains, Montana. It is evident that if these two rocks, one sedimentary, the other igneous, should be so thoroughly metamorphosed as to lose all traces of their original textures, it would be impossible to discriminate them from one another, or to say what their original status was.

Remembering the simple primary classification of the sedimentary rocks previously given, it is possible, in a very general way, to show the relation between the most common ones and their metamorphic derivatives in the following table:

Sediments.	Compacted Strata.	Metamorphic Rocks.
Gravel	*Conglomerate*	*Gneiss, and various schists*
Sand	*Sandstone*	*Quartzite* " "
Silt and Clay	*Shale*	*Slate* " "
Lime deposits	*Limestone*	*Marble* " "

In the case of the igneous rocks, recalling that they may be roughly divided into two main groups, the one chiefly feldspathic, and the other mainly of ferromagnesian minerals, we can illustrate also, in a very rough and general way, the relation between them and their metamorphic derivatives in the following table:

Igneous Rocks.	Metamorphic Rocks.
Coarse-grained feldspathic types, such as *granite*, etc...	*Gneiss*.
Fine-grained feldspathic types, such as *felsite, tuffs*, etc.	*Slate* and *Schists*.
Ferromagnesian rocks, such as *dolerites* and *basalt*.	*Hornblende-, Talc-*, (etc.), *Schists* and *Serpentine*.

A comparison of the two tables will show that gneisses and schists may have diverse origins, and the reason for this has been previously pointed out.

Another method of classification which has been recently suggested is, disregarding the origin of the material entirely, to consider only its chemical composition. According to this the metamorphic rocks are divided into groups. The earth's crust is divided vertically into zones, somewhat as described above, and the effect of the metamorphism in these zones upon each group is considered. It is found that material of a given composition yields rocks, differing in mineral composition and texture, according to the zone in which the metamorphism occurred. Thus the first grouping is a chemical one, while the subdivisions are mineral and metamorphic, and in this way the different rocks are produced and classified.

While this method may be consistent and based on scientific principles, it is not a practical one for field and megascopic use. We cannot make analyses of rocks under ordinary circumstances, nor can we, in most cases, even estimate megascopically the chemical composition from the minerals they contain, as can be done with the microscope and thin sections. And the different mineral compositions and textures pass into one another so gradually, that only in a very general way, or in specific cases, can we say whether the rocks have been metamorphosed in the zone of fracture, or the zone of flowage.

At present we are obliged, for practical purposes of field work and megascopic determination, to classify quite arbitrarily the metamorphic rocks according to their evident mineral composition or texture, or a combination of both. Sometimes, as in the gneisses, stress is laid upon the first feature; sometimes, as in the slates, upon the second one, in accordance with whichever one is the most evident and characteristic.

We have in agreement with this the following main groups of metamorphic rocks.

Grouping of Metamorphic Rocks.

1. *Gneisses* and Feldspar Rocks.
2. *Mica-schist* and *Quartzite.*
3. *Slates* and Phyllite.
4. Talc and Chlorite Schists.
5. *Hornblende Schist.*
6. *Marble,* Lime carbonate-silicate Rocks.
7. Dolomite, Magnesian carbonate-silicate Rocks.
8. *Serpentine.*
9. Iron oxides and other rocks.

By comparison it may be seen that the above is in the main a combination of the two tables previously given. The more important of the members are given in italics.

CHAPTER XI.

DESCRIPTION OF METAMORPHIC ROCKS.

GNEISS.

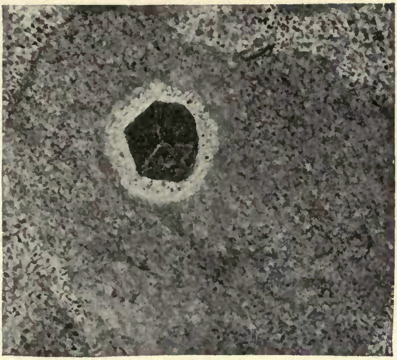
THE term gneiss is not only the name of a particular kind of metamorphic rock, but also, in a wider sense, it is used as an expression of a certain texture. Thus when we use gneiss as a name in the limited sense, we mean a rock which has the composition of granite — quartz, feldspar, and mica — with a certain foliated texture; if we say granite-gneiss, syenite-gneiss, diorite-gneiss, we use it in the wider sense, and denote rocks whose composition is indicated by the first word, and the texture by the second. The only general definition of gneiss which will cover all cases is, that they are metamorphic rocks, composed of *feldspar,* with other minerals, which have a certain characteristic texture. But, as everywhere generally used when no qualifier is prefixed, common gneiss, which is composed of quartz, feldspar and mica, as stated above, is understood, and the term is so employed in this book. If the wider sense is meant the qualifier is given.

Mineral Composition. Various kinds of *feldspar* are found in gneisses, both the alkalic and soda-lime varieties, but they can rarely be distinguished by megascopic means. The mineral is white to gray in color, or reddish, as in granite, and is apt to be in more or less round, or elongated, lenticular, formless grains; this lack of definite form makes it more difficult to distinguish from the quartz than in most granites, and the cleavage should be carefully sought. Sometimes large grains, the size of a pea, or even larger, occur, giving the gneiss a porphyritic character; if the cleavages of these are examined against the light, it may be often observed that they are Carlsbad twins. Such large crystals may indeed have been the phenocrysts of a former porphyritic granite, or they may have been feldspar pebbles of a conglomerate or arkose, or they may have been made by injected material.

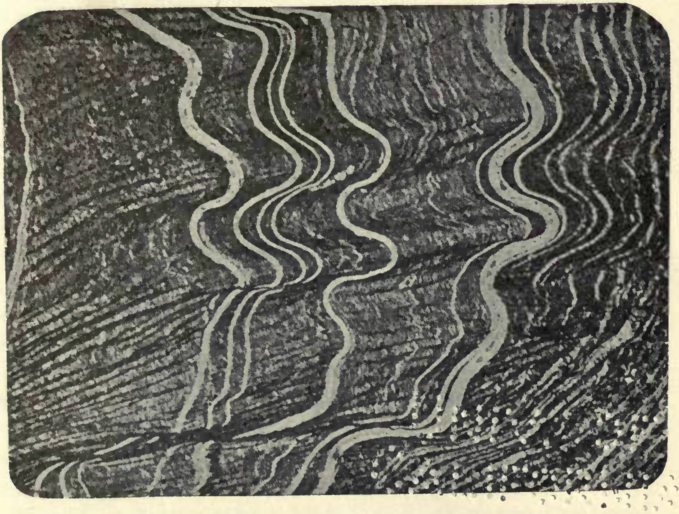
The *quartz* is also in more or less round grains or lenticular masses, or in granular aggregates with the feldspar. Its color is white or gray, sometimes reddish, rarely bluish. In the larger grains it is easily recognized by its greasy luster and conchoidal fracture.

The *mica* may be either biotite or muscovite, or a mixture of both. The biotite is black or dark brown, the muscovite is white or yellowish to light brown, sometimes pale green. The mineral does not have any distinct crystal form, but is in flakes, shreds or irregular leaves, drawn out in bands, or in thin patches. It usually lies stretched out along the structure planes of the rock, and in large part its easy cleavage, thus arranged in one direction, conditions the schistosity or cleavage, and gives emphasis to the gneissoid texture. Thus the surface of chief fracture of a flake of the rock may appear to be largely coated with mica, and, judging from this alone, one would be apt to gain an exaggerated idea of the relative amount of it in the rock; the surface of cross fracture should also be examined to gauge correctly its relative amount, as compared with the other mineral constituents. This is also especially true, in the mica schists, and in those gneisses, which, by decrease of feldspar and increase in mica, form transitions into these latter rocks. This effect is also more marked in many gneisses, because there is a tendency for the quartz and feldspar to be collected in layers, which alternate with layers of mica.

Hornblende may occur in gneisses, sometimes associated with the mica, sometimes alone, forming a special variety. It is seen in dark, prismatic crystals without good terminations, as in granite, syenite, etc. Minute crystals may be aggregated into flattened lumps and layers.



A. GARNET IN GNEISS, WITH ZONE OF GROWTH.



B. GNEISSOID CONTORTED SCHIST.

(U. S. Geological Survey.)

Besides these, many other minerals may occur in gneisses, sometimes so prominently as to form special varieties. Of these *garnet*, of a dark red common variety, is perhaps the most conspicuous. The crystals are sometimes large, as compared with the size of the other rock constituents. *Epidote* may also be discovered, as well as *graphite*, in some varieties. *Sillimanite*, a mineral with the same composition as andalusite and cyanite, is sometimes seen in gneiss, in bundles and brush-like groups of slender fibers or prisms. *Tourmaline* occurs also under circumstances similar to those which obtain in granite. In some gneisses the mica may be partly, or wholly, replaced by *chlorite*, usually from alteration.

Texture. This has been already described in large part under the general remarks on metamorphic rocks and what has been said above respecting the mica. The essence of the texture consists in the layers of mingled quartz and feldspar, which are separated by drawn out layers of mica. Where the amount of mica is small, the gneissoid texture is less evident, and it increases with the increase of mica. Sometimes these layers are thick and coarse, giving a pronounced gneissoid effect, sometimes the layers are extremely thin. In some cases the layers continue their individual character for considerable distances, in others they are very short, lenticular, and are closely interlaminated. According to these appearances, different varieties of gneiss have been named on a textural basis. The gneissoid texture is sometimes scarcely perceptible in a hand specimen, but clearly seen on a large, exposed surface of the rock. This is especially the case in rocks which were originally granites, but which, by pressure and shearing, have been converted into gneiss.

The texture described above, the banding or schistosity, may extend for long distances in straight, regular lines, or it may be curved, folded, contorted, or faulted, often in the most complex and remarkable manner, and on any scale, even to a very minute or even microscopic one. Examples of such intricately folded and compressed gneisses are seen on Plates 35 and 36. Such folding testifies in general to repeated dynamic movements, with shearing and folding, the earlier ones producing the gneissoid structure and the later ones crumpling it up, though it is possible that in some cases the two things are simultaneous.

In some gneisses, as in some granites, a definite *porphyritic* texture may be present, with large and definite crystals of feldspar, which show more or less distinct crystal form.

Such gneisses are to be generally regarded as originally porphyritic granites, which have had the gneissoid texture imposed upon them, though in some cases, it may be, that the large crystals have been formed in gneiss of a different origin by growth from injected material. Such gneisses are allied to, and may pass over into, types, which, with a short, thick, lenticular texture, contain ovoid masses of feldspar or quartz. The ovoid bodies are called "eyes" (German, *augen*), and the rocks containing them "augen-gneiss" from the German name, or "eyed-gneiss." As explained on a previous page on the texture of metamorphic rocks, they may be of quite diverse origin.

In some gneisses are to be seen pebbles of various kinds of previously existent rock masses, of granite, quartzite, etc. They are apt to be drawn out into flattened lenticular masses, but their original character is evident, and it is clear that the gneiss in such a case was originally a conglomerate, whose finer material has been metamorphosed, leaving the larger pebbles mostly unchanged, save in shape.

Color. The color of gneisses is too variable a feature to be of any value as a special character. It depends on the color of the quartz and feldspar, and on the relation of these to the amount of biotite, or other dark colored minerals, they may contain. Also, in gneisses of sedimentary origin, carbonaceous material may be present and in the form of graphitic material color the rock very dark. Hence we find them from almost white passing through light shades of red or gray into darker ones, into brown and green, and even black.

Chemical Composition. As the sources of the material from which gneisses have been made are varied, so do we find great variability in their chemical composition, so much so that this character cannot be relied upon as having any special value as one of their definite features. Since they are composed of quartz and feldspar in notable amount they must contain silica, alumina and alkalies, and they usually have also more or less iron and lime, but these oxides may vary within wide bounds, as may be seen from the following table of analyses of a few typical gneisses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I...	71.0	15.0	1.1	1.8	0.7	0.3	2.5	5.8	1.1	0.5	99.8
II..	65.1	16.4	0.9	5.6	2.4	2.4	3.3	1.9	0.7	1.3	100.0
III.	78.3	10.0	1.8	1.8	1.0	1.7	2.7	1.3	1.0	0.9	100.5
IV .	82.4	11.3	1.0	0.3	0.2	0.2	0.6	1.0	2.5	0.2	99.7
V ..	52.2	18.8	2.7	5.3	5.1	8.0	3.3	1.6	1.4	1.7	100.1
VI .	44.5	17.5	3.4	12.6	5.7	3.3	3.6	3.5	1.6	5.2	100.9

I, Granite-gneiss, Lincoln, Vermont; II, Garnet-biotite-gneiss, Fort Ann, Washington Co., N. Y.; III, Gneiss, fine grained, Great Falls of Potomac River, Md.; IV, Schistose gneiss, Marquette region, Michigan. V, Plagioclase-Gneiss, Mokelumne River, California; VI, Gneiss (Kinzigite), Schenkenzell, Black Forest, Baden.

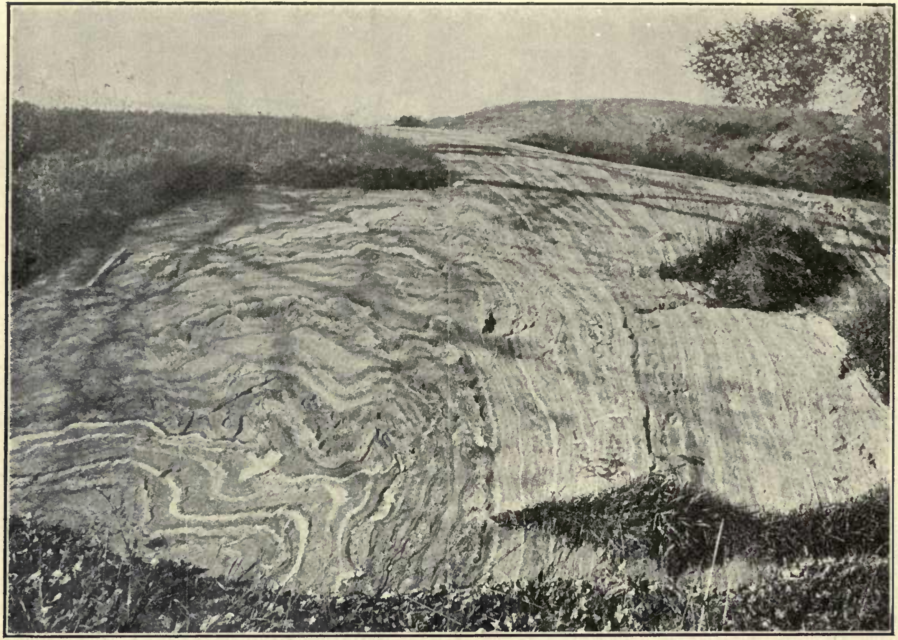
On the other hand, as stated in the introduction to metamorphic rocks, the analyses may suggest a clue to the origin of the material. Thus analyses III, IV, and VI above are quite unlike those of any igneous rock, and are almost certainly of material of sedimentary origin, while the others may be of igneous derivation.

Varieties of Gneiss. A very great number of varieties of gneiss have been distinguished by geologists and petrographers. These have been based, partly on differences in texture, such as "banded-gneiss," "lenticular-gneiss," "augen-gneiss," etc., partly on the presence of some characteristic or unusual mineral, such as "biotite-gneiss," "hornblende-gneiss," "epidote-gneiss," etc., and partly on general composition, such as "granite-gneiss," "diorite-gneiss," etc. In the latter case the term, as explained in the introductory paragraph, is used in the sense of a general textural modifier. It would not be suitable in a work of this kind to give a description of all these varieties, but a few of the most prominent may be mentioned. The textural modifications have been already sufficiently considered under the heading of texture.

Of mineralogic varieties, by *common gneiss*, or "gneiss" for short, *mica-gneiss* is meant. If further distinction is required, the kind of mica present may be stated, and we thus have *biotite-gneiss*, *muscovite-gneiss*, or *biotite-muscovite-gneiss*. If the mica is accompanied or replaced by some prominent mineral, as is often the case, other varieties are formed, such as *hornblende-gneiss*, *epidote-gneiss*, *tourmaline-gneiss*, *garnet-biotite-gneiss*, etc. The different prominent minerals, which may thus take part, have been already described under composition. Of the varieties based on general composition, it may be said that all of the different varieties of coarser-grained, feldspathic, igneous rocks may occur with pronounced gneissoid texture. In accordance with this we have *granite-gneiss* — by far the most common variety — *syenite-gneiss*, *diorite-gneiss*, and even *gabbro-* and *anorthosite-gneisses*. Sometimes this texture has been imposed upon the igneous rocks after they had solidified, by intense pressure and shearing, and sometimes while they were still soft, pasty and crystallizing, by forced differential flowage, due to various causes.

Inclusions in Gneiss. It is very common to find inclusions, or smaller rock masses, embedded in gneiss, which differ in a marked degree in mineral composition, texture, etc., from the main rock body which encloses them. Thus lenticular masses of *quartz* frequently occur, and of very variable size. They may be the remains of a quartz pebble of a conglomerate, as explained under texture, or they may have been deposited from solution in some lenticular cavity, opened in the folding of the rock masses. This case may sometimes be detected, in that the quartz mass tends to possess a comb structure, being composed of an aggregate of crystals whose prism directions are set perpendicular to the wall of the cavity.

PLATE 36.



CONTORTED GNEISS, OTTAWA RIVER, CANADA.

(After R. W. Ells.)

In many gneisses irregular spots, streaks, and lines of *pegmatite* occur, similar to those in granite. In addition to the quartz, feldspar and mica, they often contain the accessory minerals seen in granite-pegmatite dikes, such as tourmaline, apatite, beryl, garnet, topaz, etc. In the latter case they probably represent the remains of former granite-pegmatite dikes, which have been folded up or squeezed out in dynamic metamorphic processes, but not all of the pegmatitic modifications seen in gneiss are to be certainly ascribed to such an origin, for they may have been produced by secretions from later solutions of heated waters moving through the rock mass. The beautiful crystals of orthoclase, of the varieties called adular and moonstone, occurring in some gneisses, have been probably produced in this way.

Also there are frequently seen in gneiss, spots, streaks and irregularly curved and winding ribbons of white or pink felsite, or fine-grained granite similar to the aplite of granites. These may be former aplite dikes folded up, or later granitic intrusions or secretions from heated solutions. They are sometimes seen in the most complicated systems of network passing through the rock, and they may not have any definite wall against the gneiss, as is the case with regular aplite dikes. By their foldings, faultings, and contortions, they often show very clearly the movements which the general rock body has undergone.

Included masses of other kinds are also frequently met with in gneiss. Thus the streaks and smears, produced by aggregates of the dark-colored or ferromagnesian minerals, such as are seen in granites and are described as "schlieren," are found in gneiss, and may have a similar origin. Also, irregular masses, strips, and lenticular bodies of other schists occur, which, if the gneiss has been derived from a former mass of igneous rock, may have been included or enveloped fragments of the stratified beds, into which it was intruded.

While the study of thin sections under the microscope is often of great assistance to the field study of a gneiss, in the endeavor to ascertain its origin and to thus understand better its relation to other rocks, it is by no means always necessary. Very much may be done by careful observation in the field of all the facts ascertainable, and by the thoughtful correlation of these facts with one another. From place to place the rock should be minutely studied with the lens and any change in mineralogical composition or texture noted. The following embody some of the chief points which should be looked for, to distinguish rocks originally igneous from those of sedimentary origin. The igneous ones are more apt to have a uniform composition and texture over large areas. The region of the contact with other rocks should be carefully observed, to see if there are any remains of a former endomorphic contact visible, such as a diminishing of grain, or the assumption of a porphyritic texture, as well as the appearance of pneumatolytic minerals, of which tourmaline may be cited as a specially important example. The remains of former aplite dikes and pegmatite veins, as described above, should also be noted in this connection. The enveloping or bordering rocks should be carefully studied to see if, by change in mineral composition, in texture, and in the presence of tourmaline, or other pneumatolytic minerals, any remains of a former aureole of contact metamorphism may be discovered. The character of the plane of contact of the gneiss and its neighboring rocks should be examined to see, if possible, whether they are interwoven, as contorted interlaminated beds might be expected to be, or whether the gneiss cuts directly across them. In fact all of the field characters indicative of intrusion, which have been described under granite, should be looked for, under the veil which metamorphism has cast over the region under study. They may, of course, have been entirely obliterated, but some of them may persist and be valuable indicators.

In sedimentary gneisses, on the other hand, more rapid changes, from place to place, in composition and texture may be looked for, both on a large and on a minute scale. The remains of former pebbles, or small, lenticular masses of different composition indicative of them, should be sought for. The presence of carbonaceous matter, or graphite, diffused through the rock, or collected in spots or streaks, is also of use in indicating this origin. The absence of any of the signs of intrusion, and the character of the contact, as mentioned above, may also be of value in this connection. Not too much stress must be placed on the mere presence of felsitic and pegmatitic veins or dikes, as these may have been injected into sedimentary rocks, as well as into igneous ones. Their character, number, disposition, and contact wall must also all be considered in relation to the rock mass they accompany.

If, to the facts observed in the field, a chemical analysis of a well selected specimen, or series of specimens, of the gneiss can be added, this may prove in addition of great value. This has been commented on elsewhere and need not be repeated.

When all is said and done, however, it must always be remembered, as Rosenbusch, the great German petrologist, has well said, "there is no formula by which the derivation of a gneiss may be invariably determined." It must not be done on any one character alone, but all must be taken into account and relatively balanced, and even when this is done, it is impossible in many cases to say if the gneiss has been derived directly from an igneous rock, or whether the material of the latter may not have passed through an intermediate sedimentary stage.

General Properties and Uses of Gneiss. Those gneisses, which under the action of metamorphic agencies have been thoroughly recrystallized, form solid and massive rocks, whose general properties closely resemble the massive igneous ones. Thus granitic gneiss closely resembles granite, and is used in the same manner for building and structural purposes. But often gneiss contains so much mica, that it has too easy a cleavage to be of much value. In general a gneiss should be so placed, that the plane of chief fracture lies in the mortar bed with the cross fracture exposed; otherwise it is liable, like some sedimentary rocks, to split and scale badly. Those gneisses which have assumed their texture under conditions of dry crushing and shearing are very tender and friable rocks, which fall to pieces readily under the blow of the hammer, and are of little value. The granite-gneiss of portions of the Alps, and the anorthosite-gneiss of parts of the Adirondacks, are examples of this. The jointing, erosion forms, etc., of granite-gneiss are similar, in general, to what is stated under granite. So also is the weathering, and gneisses form fertile sandy soils, which pass into loamy ones, as the decay of the feldspar and its alteration into kaolin becomes more complete.

Occurrence of Gneiss. Gneiss, especially common or mica-gneiss, is one of the most common and widely distributed of rocks. The occurrence of the metamorphic rocks in general has been already commented on, and it was stated that they are found in mountain regions and in those areas where the sedimentary beds have been eroded, as a basement upon which these later rocks rest. In such places common gneiss is usually the most prominent rock. Owing to this, it is spoken of by many geologists as " the basal gneiss," or " fundamental gneiss," and as, in many places, it is clearly the oldest rock of which we have any knowledge, some believe that they see in it the primitive crust of the earth. The Archæan, as it is now used as a division of geologic time, is almost entirely composed of gneiss, and to attempt to mention all the localities of the rock, would be practically equivalent to a description of the occurrence of the Archæan. Gneisses are not of course restricted to the Archæan; they occur in later formations, into the Mesozoic. Gneisses are found all over New England, and southward along the Piedmont plateau into Georgia; in the Adirondacks; in the Rocky Mountains' region, the Sierra, and other places in the United States; they cover large parts of eastern Canada and are prominent in Scotland, Norway and Sweden, Finland, parts of Germany, and in the Alps. In all of these regions different varieties, such as hornblende-gneiss, occur associated with the common kind.

Granulite. Associated with gneisses in a number of localities is a schistose, to thin schistose, rock composed almost wholly of quartz and feldspar. It is nearly, or wholly, free from mica, and is usually of fine to dense grain, so that, except for its schistose character and place of occurrence, it is much like an igneous felsite or aplite. It is apt to carry minute red garnets, and sometimes small quantities of other minerals, such as cyanite, tourmaline, or hornblende, can be detected with the lens. Chemically, it is similar in composition to some felsites or the aplite variety of granite, and it probably represents in general former igneous rock of this nature which has been involved in the metamorphic processes. Such granulites occur in Saxony and other places in Germany, where they were first studied; in Sweden, Finland, Austria, etc., in Europe; in New England and in the Adirondack region of New York.

MICA-SCHIST.

Mica-schist is a rock which is closely related on the one hand to gneiss, and on the other to quartzite. It is not only a very common companion of gneisses, in regions of metamorphic rocks, but in many places gneiss grades into mica-schist, so that no definite line can be drawn between them. It has also many other analogies with gneiss, some of which will be presently mentioned. Of that great class of rocks known as schists, it is, excluding gneiss, if the latter be reckoned among them, the most widely distributed and important.

Composition — Minerals and Texture. The essential minerals of mica-schist are quartz and mica, and it is especially the latter which gives the rock its particular character. Different varieties of mica occur; the most common is a silvery white muscovite; biotite of a dark color is common, while the soda-bearing mica — paragonite — is rare. Muscovite and biotite occur alone, and also in combination, as in gneiss. The micas are in irregular leaves or tablets, without crystal boundaries, or in leafy or foliated aggregates; biotite and muscovite are found intergrown, and often so that they have a common cleavage. The micas lie with their cleavage planes in the direction of schistosity, and it is this which produces the extraordinary fissile character of the rock. They are also very often curved, bent, or twisted, as may be easily seen by the reflections from their cleavage surface. The cleavage of the mica is so marked that the surface of chief fracture, or the schistose plane of the rock, appears completely coated by it, and it may produce the impression that it is the only mineral present; to see the quartz, the other essential component, the cross fracture should be examined with the lens. The quartz forms irregular grains, or aggregates of grains, and these are sometimes arranged in small lenses, and sometimes in thin layers, concordant with the layers of mica.

Mica-schists, while they are very often composed of these two minerals alone, also very commonly carry crystals, often of large size, of other minerals. The most common of these is a dark red garnet, sometimes sparsely, but generally thickly, sprinkled through the rock, and varying in size from that of coarse shot to that of a plum. These garnets are often in the form of simple, rounded nodules, but in most cases they show more or less distinct crystal form, and sometimes they are beautifully crystallized in the shapes mentioned in the description of this mineral. This garnetiferous variety of mica-schist is a very common metamorphic rock; in New England it is widely distributed among the bowlders of the glacial drift.

Other minerals which occur in mica-schist, in a manner similar to garnet, are staurolite, often with garnet, cyanite, epidote, andalusite, and hornblende. These sometimes are in large and well-formed crystals, which, especially staurolite, andalusite, and cyanite, are not infrequently colored dark, by included carbonaceous matter. Graphite occurs in some mica-schists in quantity sufficient to produce a distinct variety. Graphite is such a strong coloring matter, that a relatively small amount will cause the rock to appear as if almost entirely composed of it; in consequence unsuccessful attempts have been made in places to exploit such schists for graphite.

Hornblende, when it occurs, is in dark-colored prisms; by its increase in amount transitions into amphibolite or hornblende schist are formed.

Cyanite, andalusite, and staurolite occur in prismatic crystals, which may attain a length of several inches. Their formation is contemporaneous with the metamorphism of the rock, and they produce a pseudo-porphyritic texture as previously explained on page 342. Another variety of mica-schist is one which contains more or less calcite mingled with the quartz; it is readily detected by its effervescence with acids. This variety is especially apt to contain accessory garnet, epidote, hornblende, etc.

The parallel texture of the rock is its especial feature, and its ready fissility is produced by the mica. If the components are in thin, parallel layers, the surface of rock cleavage is smooth and flat; if the lenticular arrangement of the quartz is prominent, the surface is uneven or lumpy. Frequently the surfaces of schistosity are bent, folded and crumpled, showing pressures and shearing secondary to its production.

Chemical Composition. As in the gneisses, the chemical composition of these rocks is too variable a feature to be of specific value. This comes from the natural variability in the composition of the sediments from which they are formed. In addition, not many of these rocks have been chemically investigated, and some of the older analyses have been very poorly executed. It is clear, however, that they must contain silica, alumina, and potash, to form the quartz and mica, and also magnesia and iron, if biotite is present. The excess of magnesia over lime, taken with the high silica, is a character foreign to igneous rocks, and is clearly indicative of sedimentary origin. They are probably formed mostly by the metamorphism of feldspathic sandstones. Two analyses of typical samples carried out in the laboratory of the United States Geological Survey are here appended.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	H_2O
64.7	16.4	1.8	3.8	3.0	0.1	0.1	5.6	3.1	0.8	99.4
64.8	14.4	1.8	4.5	2.3	2.3	1.4	5.0	2.0	1.9	100.4

General Properties. The *color* of these rocks varies from very light, through gray, yellow, or brown tones, into very dark, depending on the proportions of light and dark mica, the presence of carbonaceous material, and in part on the amount of alteration of the iron-bearing biotite. Some pure muscovite schists are almost silvery white or light gray. The hardness and firmness of the rock depend on the proportion of mica; the more this is present, the softer and more easily cleavable it is. For this reason they are of little or no value for practical purposes. *Inclusions* of various kinds occur in mica-schists as in gneiss, thus veins and lenticular masses of quartz, deposited from solution in cracks and cavities opened by movement and foldings of the rocks, are common. They also contain in places lenticular masses of other schists, which may vary from very small to huge dimensions. And sometimes they are penetrated by seams and patches of granite, felsite, and pegmatite as the result of granitic injections. With respect to the *alteration* of mica-schist, the varieties composed of muscovite are chiefly mechanically disintegrated by the action of weathering without much chemical change. The muscovite resists alteration energetically, and the gravelly or sandy soils formed, are in consequence filled with its sparkling flakes. Where much biotite is present it alters easily; the rocks turn yellow or brown, lose their luster, and eventually much limonite is separated out.

Varieties and Occurrence. The varieties composed chiefly of muscovite, or with associated garnet, are the most usual kinds, and are found all over the world as common rocks in metamorphic regions, and are generally associated with gneisses. They cover large areas in New England and extend southward to Georgia. Biotitic varieties are also very commonly found with them. Staurolitic mica-schist occurs in many places in New England, and in Maryland, and elsewhere along the Piedmont plateau; it is found in Scotland and various localities in Europe, in Brazil and elsewhere. Cyanite-mica-schist occurs in various places in New England; a variety in which the mica is paragonite comes from the St. Gothard region in the Alps, and is seen in mineral collections on account of the beautiful crystals of cyanite it contains; the common kind with muscovite is found in many places. Hornblendic mica-schists occur as included lenticular masses, often of large dimensions, in various places, in the ordinary mica-schists. Graphitic mica-schist is found in Connecticut and other places in New England, various localities in Germany, Norway, etc. Andalusite-mica-schist occurs in the White Mountains in New England, in Scotland, Spain, Germany, etc.

An interesting variety is the conglomerate-mica-schist, in which the rock contains pebbles of quartz, granite, and other rocks which are very apt to be flattened, lenticular, or drawn out by pressure and shearing. It is closely related to the conglomerate-gneiss previously described and has had a similar origin. Such rocks occur in Massachusetts, in Vermont, Scotland, Sweden, etc.

Transitions and Relation to other Rocks. The gneisses formed from sediments and the mica-schists have both been made from similar rocks; from feldspathic sandstones, shales and conglomerates. In the mica-schists the feldspar has been converted into mica; in the gneisses it has mostly persisted or been recrystallized. It is not intended in this statement to affirm that this is the only origin for mica-schists, only the most usual one; they may have been formed in some cases from quartzose-feldspathic igneous rocks, though positive evidence on this point is wanting. In this connection what is said elsewhere of phyllites should be consulted. On the whole it would seem most probable that the gneisses have been formed most often from the conglomerates and coarser-grained sandstones, the mica-schists from the finer-grained ones, and from the shales, though many exceptions must occur.

It is therefore easy to understand that many mica-schists contain more or less of feldspar grains among those of quartz, which are difficult to detect without the aid of microscopic investigation. These may increase in amount until the rock passes over into a gneiss, and no hard and fast line can be drawn between them, as previously stated. The decision as to whether a given rock should be classed as a gneiss or mica-schist is often a very difficult thing to make on purely megascopic grounds; in general if the amount of mica is large, and little or no feldspar can be detected with the lens, it is best to classify it as a mica-schist; if the amount of mica is small and feldspar can be seen, to define it as a gneiss.

On the other hand, in proportion as the original sandstones were more and more purely composed of quartz grains there would be less and less of mica made, and in this way formal transitions into quartz schist and quartzite are produced in their metamorphic representatives. We thus see that gneiss, mica-schist, and quartzite form a graded series whose divisional lines must be purely arbitrary.

Again, as the rocks become finer and finer in grain and in texture, the mica-schists pass into micaceous slates and so on into slates, and this becomes more marked if the amount of carbonaceous matter increases, as it tends to mask the mica. The divisional line thus becomes an arbitrary one in this case also.

QUARTZITE.

Quartzite is a firm, compact rock, composed of grains of quartz-sand united by a cement consisting of the same material, that is, of deposited quartz. They are in general metamorphosed sandstones, and while no hard and fast line can be drawn between the two rocks, since all degrees of transition can be found between them, the quartzites are much harder and firmer than the sandstones; the latter have a more or less sugar-granular feeling and appearance; the individual grains are distinctly visible to the eye or lens, while in the quartzites the fractured surface is uneven, splintery or conchoidal; the luster vitreous or greasy, like that of quartz, and the grains are imperceptible or nearly so. This difference arises chiefly from the fact that in breaking the sandstone the fracture takes place in the cement, leaving the grains unaltered and outstanding, while in quartzite the grains are so firmly cemented, that there is nearly a homogeneous substance formed and the fracture takes place through cement and grains alike. This difference will serve as a practical distinction between the two rocks.

Minerals and General Properties. While some quartzites are very pure in mineral composition, others carry in greater or less abundance other minerals, which may be in part remains of original mineral grains, such as feldspar mixed with those of quartz, or new ones which have resulted from the metamorphism of the clay or lime cement, which formerly filled the interstices between the grains of the sandstone. Such are muscovite, chlorite, cyanite, epidote, etc. Iron hydroxides may be converted into magnetite or hematite, and carbonaceous substance into graphite. These resultant minerals are usually of microscopic size, and may give the rock a distinct color — green, blue, purple, black, etc.; sometimes they are large enough to be clearly seen with the lens. The most important of them is muscovite, which, as it increases in amount, gives the rock a more schistose character, through which it attains a capacity for cleavage along the planes of the mica. Eventually this produces a transition into mica-schist, as previously explained under that rock. The normal *color* of quartzite is white, light-gray or yellowish into brown, but these are often modified by included material acting as a pigment, as explained above. The *jointing* of quartzite is usually platy, but sometimes very massive, and such rocks are in some places quarried and furnish good material for structural purposes.

The chemical composition of a pure quartzite is nearly that of silica alone, but as more or less clay or calcareous material was mixed with the sand, small amounts of alumina, iron, lime, and alkalies appear. This is illustrated in the contrast of the two analyses quoted below.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	Total
I...	97.71	1.39	1.25	—	0.13	0.18	—	—	—	100.66
II..	74.22	10.61	7.45	0.85	1.48	0.56	2.12	1.08	1.79	100.16

I, Pure quartzite, Chickies Station, Pa.; II, Impure quartzite, Pigeon Point, Minn. Contains small quantities of feldspar, mica, chlorite and magnetite.

Varieties. The different varieties of quartzite are chiefly those which are occasioned by the presence of some included substance. Thus we have epidotic quartzite, graphitic quartzite, sillimanite-quartzite, and many others. Micaceous quartzite is also called quartz-schist. In very strongly folded and compressed mountain regions even pure quartzite may suffer such shearing as to break and crush the original grains and impose a more or less schistose structure. Such rocks are called *stretched* quartzites. In some places these rocks contain pebbles, of varying sizes, which retain their original shape and are sometimes by pressure and shearing reduced to lenticular, ovoid, or cylindrical bodies. These are called *conglomerate-quartzite* and were formed from gravels, like conglomerate-gneisses and conglomerate-mica-schists.

Oölitic quartzite is a variety consisting of rounded grains, composed of chalcedony, a slightly hydrated form of silica, deposited around fragments of quartz which serve as nuclei. It resembles the roe of a fish, and if the globules are sufficiently large, their concentric structure can be plainly seen with a lens on the broken or polished surface of the rock. Such quartzites have been found at State College, Pa., and in Sumatra. *Buhrstone* is a name given to a variety of quartzite which is full of long, drawn out hollows or pores. Notwithstanding the porosity, it is quite firm and its hardness and toughness have caused its use as a millstone. It is thought to have been originally more or less of a limestone, filled with fossils, which, by the action of solutions containing silica, has been converted into a quartzite, consisting mostly of chalcedony, whose cavities represent the leached out fossils. It occurs in western Massachusetts, Georgia, South Carolina and in the Paris Basin in France. It is chiefly of Tertiary age.

Occurrences. Quartzite is a widely distributed rock, mostly among the older metamorphosed strata. Thus it is common in eastern North America, in the Rocky Mountains Cordillera and in various localities in Europe and other parts of the world. The occurrence of some special varieties has been already mentioned.

Alteration. On account of the insoluble, unyielding nature of its constituent grains and their cement, quartzite resists erosion and the atmospheric agencies well, and, where it is prominent in mountain regions and areas undergoing denudation, it forms prominent features of the landscape, bold ledges, cliffs, castellated crags, spires, etc.

Eventually the rock breaks down into sandy soil of poor quality.

Distinction from Other Rocks. Quartzites, which are very homogeneous appearing rocks, may be confused, in the outcrop or hand specimen, with some limestones or felsites of a similar color and texture. From the former they are easily told by a test of the hardness, or by lack of effervescence with acid; from the latter, in the field by the different mode of geological occurrence, by the cleavage of the feldspar if visible under the lens, or by blowpipe test. It should be remembered that the chief minerals composing these three rocks are quartz, calcite, and feldspar respectively, and they should be tested accordingly.

SLATE OR ARGILLITE.

Slates are dense, homogeneous rocks, of such fine texture that the individual mineral particles composing them cannot be distinguished by the eye or lens, and characterized by a remarkable cleavage, by means of which they split readily into broad, thin sheets, which, as is well known, may be used for a variety of purposes.

The slates represent in metamorphic form the finest material of the land waste by erosion, which, among the unmetamorphosed stratified rocks, appears as clay, shales of various kinds, etc., as previously described. With such material more or less volcanic dust and débris, or tuffs, may be mingled. The cause of the slaty cleavage is discussed in a following paragraph. The difference between slate and shale has been discussed in the description of the latter rock.

Mineral Composition and Other Properties. The mineral particles are so fine in slate that the composition from the megascopic standpoint is not a matter of importance. It may be mentioned, however, that since the clays, silts, etc., from which they are formed come from a great variety of sources, so the microscope detects in them many and varied minerals, the chief of which are quartz, mica, chlorite, carbonaceous substance, etc. The kaolin and feldspar particles, which one might naturally expect, are rare and appear to have been converted into other minerals. They not infrequently contain crystals of pyrite, readily seen with the eye or lens, which may attain large size, sometimes as distinct crystals, sometimes as concretions, or replacing fossils. Veins, lumps, and lenses of deposited quartz are also common in them, those of calcite more rare. The *color* is chiefly gray, to dark gray, to black, according to the amount of carbonaceous substance, but they are often green from chlorite, or red, purple, yellow, or brown, from the oxides of iron. The surface of the slaty cleavage is apt to have more or less of a silky luster, sometimes scarcely perceptible; the cross fracture has a dull surface. While the rock is firm and never friable, it is also rather soft, so that it may be quite readily cut, a feature of great value for technical purposes. The specific gravity of an average slate is about 2.8. The chemical composition is shown in the following analyses of typical examples, made in the laboratory of the U. S. Geological Survey.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	C	XyO	Total
I	59.7	17.0	0.5	4.9	3.2	1.3	1.4	3.8	4.1	0.5	3.8	100.2
II	67.6	13.2	5.4	1.2	3.2	0.1	0.7	4.5	3.3	—	0.7	99.9
III	59.8	15.0	1.2	4.7	3.4	2.2	1.1	4.5	3.8	—	4.3	100.0
IV	56.4	15.3	1.7	3.2	2.8	4.2	1.3	3.5	4.8	0.6	6.5	100.3
V	60.5	19.7	—	7.8	2.2	1.1	2.2	3.2	3.3	—	—	100.0

I, Black roofing slate, Benson, Vermont. XyO = TiO_2, P_2O_5, CO_2, FeS_2, etc.; II, Red roofing slate, Washington Co., New York State; III, Green roofing slate, Pawlet, Vermont, CO_2, 3.0; IV, Black roofing slate, Slatington, Pennsylvania, CO_2, 3.7; FeS_2, 1.7; V, Roofing slate, Wales.

The general predominance of magnesia over lime in the analyses, as well as the small amount of the latter, shows that the soluble lime silicates have been mostly dissolved out of the silt in the process of erosion and laying down of the sediments. The presence of carbon in the black varieties, and of ferric iron in the red, is to be noted.

Varieties. Roofing slates are compact, very fissile varieties which split with a smooth, even cleavage. All the different colors are used, but the most common is a dark gray. Some slates fade when taken from the quarry, on continued exposure, through incipient alteration and the possibility of this can only be determined by practical trial. The presence of pyrite in any notable quantity is very prejudical, as this substance on exposure quickly alters and gives rise to rusty stains. The slates used for blackboards and ciphering are the blackest and most compact kinds. *Calcareous* slates are those which contain a good deal of intermingled calcite, or chalky material, which may rise to 30 per cent of the whole; they represent slates which have been formed from original marls.

Cleavage of Slates and its Origin. The cause of slaty cleavage has occasioned much speculation and has been the subject of investigation, both experimental and mathematical, as well as geological, by a number of scientists. From this work it has become clear that it is the result of great pressure upon the material and that the planes of cleavage are at right angles to the direction of pressure. When the fine-grained sediments are subjected to intense pressure, unevenly shaped particles tend to rotate, so that their longer axes are perpendicular to the direction of pressure; they also tend to become flattened perpendicularly to it. This tends to give the rock a grain, an arrangement of particles, by which it tends to split more readily along such a direction than in any other. Moreover the rock minerals, which naturally tend to be flattened or elongate in the shape of their particles, such as the micas, kaolin, hornblende, chlorite, etc., possess an excellent cleavage parallel to the elongate or flattened directions, and this is a great help in promoting the capacity of the rock cleavage. Slaty cleavage is thus partly molecular, or mineral cleavage, where it passes through a single mineral particle, and partly mechanical where it passes between arranged, unlike mineral particles. Not necessarily all of the minerals whose cleavage and arrangement induce the slaty cleavage are original; some of them, micas for example, may have been formed by the metamorphism accompanying the pressure.

The planes of cleavage do not necessarily bear any definite relation to those of original bedding. The beds were laid down horizontally and the direction of pressure is also usually horizontal; the cleavage planes are at right angles to this, and may therefore cut the bedding at right, or highly inclined, angles. But, as the beds may be folded before the pressures become intense, the cleavage planes may pass through the bedding at various angles, although they themselves are strictly parallel, as seen in the diagram, Fig. 74.

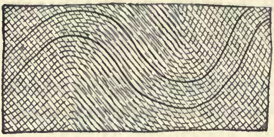


Fig. 74. Slaty Cleavage in Folded Beds.

Slates, in addition to their cleavage, are intersected by cross joints which are frequently so numerous as to divide them into small blocks and prevent their technical use. They generally form systems intersecting at definite angles. In the older mountain ranges the slates are frequently crumpled by repeated movement and show this upon their cleavage surfaces.

Occurrence. Slates are common rocks in metamorphic regions and range geologically from the Algonkian up to recent periods. In eastern North America they are chiefly Paleozoic and have an extensive developement in Maine, in Vermont, in Pennsylvania, and in Georgia. They are also extensively distributed in the Lake Superior region and in the older ranges of the Rocky Mountains Cordillera. They are found in southern England, in Wales and in many other parts of Europe.

Phyllite. Closely connected with slate by intermediate types are a group of rocks to which the name of phyllite has been given. The name means " leaf stone " and is used on account of the remarkable cleavage of the rocks, by means of which they split into exceedingly thin sheets, in typical examples. The surface is sometimes flat, sometimes curved, folded, or crumpled by crustal movements. It differs from ordinary slate in containing a larger amount of mica, or at all events the mica is in larger flakes, and is more evident, giving the surface of cleavage a shimmering or micaceous appearance, and thus furnishing a transition form between slate and mica-schist. The mica is a fine, scaly, silky variety of muscovite to which the name of *sericite* has been given.

Quartz is the other chief mineral and may sometimes be seen on the cross fracture. Rocks, which in this country have been called "hydromica-schists," are in large part such phyllites. Their color is sometimes pure white, more often tinged with reddish, yellowish, or greenish tones, and sometimes dark colored, or black, from pigments, like those of slate. They are apt to have a soft talcy or greasy feel, and to be more brittle than slate, and to lack its toughness and firmness. Sometimes they contain visible crystals of pyrite, garnet, and other minerals.

The origin of phyllites, as shown by the researches which have been made upon them, is a varied one; in some cases they represent sedimentary material which has been metamorphosed, like the slates, but has attained a more complete degree of recrystallization than they have. On the other hand a considerable part of the phyllites represent original felsites — igneous rocks — which have been subjected to the energetic operation of metamorphism through dynamic forces, to pressure and great shearing, aided probably by liquids and heat. Their feldspars have been largely, if not entirely, converted into mica, and a thin schistose or slaty cleavage has been imposed upon them. In some extreme cases the rock appears as if wholly composed of this silky mica. The chemical analyses of these rocks show them to have compositions similar to that of many felsites or felsite tuffs.

Porphyroid — Sheared Felsites. In many places where phyllites occur, they may be traced into types which are firmer, with less pronounced but yet distinct cleavage, and which contain visible phenocrysts of quartz and feldspar, similar to those in felsite-porphyries (embedded in the phyllitic ground mass). Such rocks have been termed *porphyroid*. These again may be further traced into undoubted felsites which still retain the phenocrysts, flow structures, spherulites, etc., characteristic of lavas, or the broken, angular, fragmental features of tuffs and breccias, in spite of the slaty cleavage, which to a greater or lesser degree, has been imposed upon them by the dynamic movements and shearing to which they have been subjected. These again may be followed into undoubted, unsheared felsites. Rocks with these characters, in their varied types as described above, occur in various places among the older metamorphosed Paleozoic areas of eastern North America, in Maine, at South Mountain, Pa., in Virginia and North Carolina, in Wisconsin, the Lake Superior region, etc. They have been found of various ages in Great Britain, Germany, the Alps and other places in Europe.

In Sweden such ancient felsites and felsite tuffs, hardened and more or less metamorphosed, have been termed *hälleflinta*.

It is only in comparatively recent years that such altered igneous rocks, with more or less schistose appearance and cleavage, have been recognized and their significance appreciated. The older geologists, confused by their cleavage, regarded and mapped them as slates and considered them as of sedimentary origin. They are of interest, because, as stated in the introduction to metamorphic rocks, these latter comprise material both of igneous and sedimentary origin. Of the feldspathic, igneous rocks, the coarser-grained ones, like granite, as we have seen, yield gneisses; the compact felsites and their tuffs under the metamorphic agencies of pressure, shearing, etc., are turned into phyllites, porphyroids, and compact slaty rocks, according to the degree to which these agencies have acted. The igneous ferromagnesian rocks we shall see later among the amphibolites and other schists.

TALC-SCHIST.

Talc-schist is a rock of pronounced schistose cleavage and character, in which talc is the predominant mineral. The talc is present in fine scales to coarse foliated aggregates. Other minerals also occur in different varieties of the rock, such as quartz in grains, lenses, and veins; or magnetite and chromite in black specks and grains; hornblende, usually in white or green prisms, or crystals of enstatite; chlorite mingled with the talc, etc. The color is usually light, white to pale green, or yellowish, or gray; sometimes dark gray or greenish. The rock is soft and the talc gives it a greasy feeling, and often a pearly or tallowy appearance on the cleavage surface. In addition to its micaceous appearance and soft greasy feel, the talc is easily told by its infusibility before the blowpipe, and its insolubility in acids. The rock cleavage is sometimes thinly fissile, sometimes thicker, and sometimes cleavage is nearly wanting, the rock is more nearly massive, is compact, and has a lard-like or wax-like aspect, and approaches soapstone in character. Chemically, these rocks consist mostly of silica and magnesia with small amounts of water and other oxides.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	$Na_2O + K_2O$	H_2O	Total
I...	58.7	9.3	4.4	—	22.8	0.9	— —	4.1	100.2
II..	53.3	4.4	5.8	1.0	29.9	1.5	1.5	2.6	100.0

I, Talc-schist, Falun, Sweden; II, Talc-schist, Zöbtau, Moravia, Austria.

The composition is quite similar in its general features to that of the peridotites among igneous rocks, as may be seen by reference to their analyses.

The talc-schists undoubtedly represent material which was sometimes of igneous origin, peridotite, pyroxenite, or dunite, and sometimes of sedimentary origin, dolomitic, ferrugineous marls, etc. It may not be possible from field work and an inspection of specimens alone, unless aided by chemical analyses and microscopical study, to decide in any given case which origin the material had, and sometimes not even then. The presence of chromium, either in the form of chromite or of secondary minerals derived from it, such as kämmererite or fuchsite (a variety of muscovite green from chromium), is indicative of igneous origin, while that of much quartz and dolomite mingled with the talc, which produces the variety of talc-schist called *listwänite*, would be on the other hand more indicative of a sedimentary one.

Talc-schists do not form important formations like gneiss, mica-schist, and slates, but are limited in occurrence, being found as interbedded layers or inclusions, chiefly as lenticular masses, in other metamorphic rocks, and are really not very common. They show transitions in places into other rocks, such as chlorite-schist, crystalline dolomite, quartzite, etc. Such transitions, or the lack of them, may furnish useful hints in regard to their origin in particular cases. In eastern North America talc-schists occur, associated with other metamorphic rocks, in Canada, in the New England states, in northern New York, and south to Georgia. They are also found in the Rocky Mountains region and in the Pacific states, California, Oregon, etc. In Europe they occur in the Alps, Germany, and various other places, in Sweden, Finland, etc. They also occur in Brazil and other parts of the world. Their occurrence, though not generally of wide geologic interest, is important because they furnish a source of supply for talc, which is used for a variety of purposes.

CHLORITE-SCHIST.

These rocks are schists which have the mineral chlorite as their chief determinant mineral. It occurs as fine, scaly aggregates, sometimes too fine for the individual scales to be seen by the eye; more rarely in foliated to coarse foliated aggregates. It is sometimes thinly, sometimes thickly, schistose, and in some cases almost massive; and although the rock is very soft and may be readily cut, it is very tough in the more massive varieties. The color varies through different shades of green, yellow-green, to dark green. Different minerals are apt to accompany the chlorite, some of which may be in megascopic sizes; of these may be mentioned magnetite, often in fine crystals; hornblende in slender needles or prisms; corundum and cyanite in some cases; quartz, which is generally in veins and lenses; epidote in grains and crystals; in some instances graphite, calcite, dolomite, etc. The chemical composition of these rocks is very variable, so far as is known, for not many have been investigated; it indicates that they have resulted from several different sources, as seen in the following analyses.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
49.2	15.1	12.9	—	5.2	10.6	3.6	1.5	1.9	—	100.0
26.2	23.7	15.7	14.5	8.3	1.7	0.5	0.6	7.3	0.8	99.3

I, Chlorite-schist, east of Rotön, Sweden; II, Chlorite-schist Benguet, Luzon Island, Philippines.

No. I has a composition very similar to that of the group of igneous rocks known as gabbros, as may be seen by reference to their analyses, and to which also the dolerites and basalts belong, these being merely textural varieties of magmas similar to gabbros. No. II, on the other hand, is very different, and does not correspond to any igneous rock; it suggests rather a very ferrugineous clay.

The chlorite-schists are of wide distribution, forming subordinate layers or masses in the midst of gneisses, mica-schists and other such rocks, characteristic of metamorphic areas. Thus they occur in Canada, New England, New York, Pennsylvania, etc. They are also common in Europe, in the Alps, Germany, Sweden and other places.

Greenstone. Transitions of chlorite-schist into mica-schist, into slates, into schistose serpentine, and into hornblende-schist occur in places. Under the description of gabbro and of dolerite it was mentioned that these rocks by alteration, through processes of regional metamorphism, passed into hornblende-schists and into so-called " greenstone " or " greenstone-schist." In such cases the original ferromagnesian minerals, or the hornblende produced from them, have been largely changed by alteration into chlorite which gives the rock its green color. Such greenstones (if massive), or greenstone-schists (if schistose), which thus represent altered dolerites, basalts, and gabbros, form transition types to chlorite-schist. The alteration of hornblende in diorites to chlorite also produces greenstones. It is conceivable that a dolerite might pass directly by alteration into a chlorite rock, or greenstone, and thus be of massive character, or it might be first changed into a hornblende-schist and this secondarily alter into a chlorite-schist. But since hornblende-schists are produced, not only from igneous but also from sedimentary beds, as described in the account of these rocks, the mere fact that transitions from hornblende-schists into chlorite-schists occur does not alone prove these latter have been derived from igneous rocks in any given case. Transitions from dolerite into chlorite rocks, or greenstone-schists, have been observed in many regions; in Michigan, Maryland, Connecticut, in the south of England, in the Alps, Germany, etc. A greenstone-schist from the Menominee River, Michigan, which is known to be an altered dolerite, has the following composition.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	CO_2	Total
44.5	16.4	5.1	5.5	7.5	7.9	2.6	0.5	5.0	5.4	100.4

It is composed of chlorite, with some feldspar, quartz and calcite. This should be compared with the analyses of gabbro which represent the gabbro-dolerite group.

The greenstones vary in color from pale gray-green through yellowish green to dark green. The color depends on the proportion of chlorite to other minerals. They are generally too compact for the megascopic determination of the individual mineral particles. They are generally rather soft rocks. Sometimes, when the original dolerite or basalt was an amygdaloid, this amygdaloid structure is retained and the rock is filled with little balls of calcite or quartz. In other cases, where the rock has been strongly sheared, these have disappeared, but are still represented in the schist by ovoid spots of a different color and mineral composition from the main mass. In some rare cases they have been replaced by ores. The amygdaloidal structure is a good proof of the original igneous character of the rock.

Soapstone, Steatite. As an appendix to talc and chlorite-schists may be mentioned soapstone or steatite, a massive rock, usually of a gray or green, but sometimes of a dark color; the lighter colors often with a silvery or shimmering fracture surface. It is very soft, easily cut or worked, without cleavage or grain, and resists well heat and the action of acids. For these reasons it has been extensively used in prehistoric times for the manufacture of pots and other vessels, and is employed at present in table tops, sinks, and other interior fittings where its qualities render it valuable. It is usually a variable mixture of interwoven scales of talc and chlorite mixed with various minerals; in some cases carbonates are present. The better qualities incline more nearly to pure talc. The minerals are in general too fine for megascopic determination. It occurs in connection with talc and chlorite rocks, and sometimes with serpentine, in various parts of the world, in areas of metamorphic rocks.

AMPHIBOLITE OR HORNBLENDE-SCHIST.

The amphibolites are a large group of metamorphic rocks whose distinguishing characters are, that they consist partly or largely of hornblende, and that they possess a more or less pronounced schistose structure. There are a number of varieties in the group, depending on the kind of hornblende present, and on the minerals associated with it, so that it is difficult to give a general description which will cover all cases. It is best therefore to describe the most common kind first, and then give a brief mention of some of the less common varieties.

Common hornblende-schists or amphibolites are rocks which vary in color from green to black; the green is of varying tones, clear light green, gray-green, yellowish green to dark green, greenish black to black; the darker colors are more common. The color is given by the hornblende, though in a considerable degree, in some cases, it is influenced by admixed chlorite. The grain of the rocks varies from coarse to fine, the latter being more common. When coarse, the hornblende, which is almost always present in slender prisms or blades and rarely in grains, is easily recognized by the eye from its form and bright, good cleavage. In such cases the prisms may be an inch or more in length and have the thickness of a slender match stick; from this, in the finer-grained types, they sink to tiny needle- or hair-like prisms which can only be seen by careful observation with a good lens. The prisms are usually arranged in the direction of schistosity and thus approach parallel positions; it is this which chiefly gives the rock its cleavage. It also gives the rock, especially in the finer-grained types with needle-like prisms, a shimmering or silky luster on cleavage surfaces, which is rather characteristic. In some cases the grain is so extremely fine that not even with the lens can the individual minerals be seen; such rocks may appear very much like slates, and are indeed difficult to distinguish from them; they are however, not very common types.

The amphibolites are rather hard rocks, not easily scratched by the knife. In the more schistose types they are brittle, but as they become more massive in character they are very tough and difficult to break. They are heavy, the specific gravity ranging from 3.0–3.4.

In addition to the hornblende other minerals are present in varying kinds and quantities; prominent ones are quartz, feldspar, and mica. The quartz and feldspar in grains are best observed with the lens on the cross fracture; often they are too fine and too much masked by the hornblende to be seen; the quartz also at times forms little lenses or masses, or fills fractures in the shape of veins, as in other metamorphic rocks, and has then been secondarily deposited from solutions. The mica can be generally seen on the surface of chief fracture; both biotite and muscovite occur and may increase to such an extent as to produce formal transitions to mica-schist.

Other minerals which may be detected megascopically are iron ore, pyrite, garnet in small dark red crystals, chlorite, calcite; the latter sometimes in veins, etc., like quartz. Pyroxene, epidote, and other minerals occur, but partly on account of the fineness of grain, and partly on account of their resemblance to hornblende, it is usually impossible to detect and identify them without microscopic study.

The chemical composition of amphibolites has not yet been as thoroughly investigated as it should be, but what has been done shows, in agreement with facts to be presently mentioned, that the origin of these rocks is various. The following analyses will do for examples.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I...	49.9	15.5	3.0	8.0	7.8	8.9	3.3	0.7	1.5	1.7	100.3
II..	50.4	13.3	6.3	9.3	5.6	7.9	2.1	1.1	1.7	2.0	99.7
III.	55.0	2.9	0.8	6.3	21.0	11.5	0.3	0.2	1.0	1.5	100.5
IV .	55.6	16.3	1.2	7.2	5.6	9.2	0.9	0.2	3.1	1.0	100.3
V ..	45.6	14.2	1.2	9.8	6.8	2.3	1.6	1.2	5.1	12.6	100.4
VI .	52.4	13.6	2.7	9.8	5.5	10.0	2.3	0.4	1.7	1.6	100.0

I, Thin schistose amphibolite, Whitman's Ferry, Sunderland, Mass.; II, Amphibolite, Crystal Falls district, Michigan; III, Grass-green Amphibolite, Chiavenna. XyO = Cr_2O_3; IV, Amphibolite, Goshen, Massachusetts; V, Amphibolite, pyritiferous, Conrad Tunnel, Ophir district, California. XyO = Pyrite 7.9, CO_2 3.0, $TiO_2$1.1, plus traces; VI, Olivine-basalt, main lava flow, Pine Hill, South Britain, Connecticut.

Of these analyses Nos. I and II have compositions very much like that of the gabbro-basalt magmas, as may be seen by comparison with No. VI; No. III has the general composition of the peridotite-pyroxenite group of igneous rocks and may be compared with Analysis No. III of that group. The presence of Cr_2O_3 in III is also significant of an igneous origin. On the other hand No. IV is thought on geological grounds to be derived from an impure limestone, probably full of clay, and this supposition is rendered probable by the fact that the high alumina is accompanied by an almost entire lack of alkalies, a feature not seen in igneous rocks. In No. V, while alkalies are present with the alumina, high magnesia and ferrous iron are not accompanied by high lime and these make a combination not seen in igneous rocks. Compare again No. VI. This rock, No. V, is probably derived from an impure ferrugineous arkose or silt.

Origin of Amphibolites. As just shown, the composition of amphibolites sometimes corresponds with that of igneous rocks, and sometimes does not, and this agrees with the results of geological investigation in the field. For in some places we find them under conditions which strongly suggest their derivation from igneous rocks, and in other places such evidence is either wanting, or the contrary is indicated. The use of the microscope on thin sections, by which the inward textures and associated minerals may be seen, also leads to the same conclusions.

Under the description of gabbro and dolerite it was mentioned under alteration, how these rocks by pressure and shearing became converted into hornblende-schist or amphibolite. Gradual transitions, without geological break, from one kind into the other, are found. Thus as the feldspathic igneous rocks give rise to gneisses, phyllites, etc., so the ferromagnesian, especially the pyroxenic, igneous rocks give rise especially to hornblende-schists, and also to talc-schists, chlorite-schists, and to serpentine.

Sedimentary beds of impure mixed character, such as limestones containing sand, clay, and more or less of the hydroxides of iron, limonite, etc., or marls of a somewhat similar nature, if subjected to metamorphism might, under suitable conditions, be converted largely into hornblende, mixed with other minerals. In this case the volatile constituents — the water, carbon-dioxide, etc., — are mostly driven out; the bases, lime, iron, magnesia and alumina, combine with the acid silica, to form silicates, of which hornblende is the chief and determinant one of the resulting rock. Thus hornblende-schists result from the metamorphism of sedimentary strata, and may be one form of the alteration of limestone, as described later under marble.

Varieties of Amphibolite. In the midst of gneisses and mica-schists amphibolite sometimes assumes a very massive character. The prisms and grains of hornblende, instead of being arranged in parallel position, and thus producing a schistose cleavage, are interwoven without arrangement and cleavage is wanting. Especially in such massive types is the hornblende liable to be accompanied by feldspar. If the feldspar should increase and dominate, transitions to hornblende gneiss would be produced. There is a tendency on the part of some to restrict the term amphibolite to such massive varieties and to use hornblende-schist for those with distinct cleavage, but this distinction has not yet come into general use.

Eclogite is a variety of hornblende-schist of a rather light green color sprinkled full of red garnets. In the typical examples of this rock the hornblende is accompanied, or more or less replaced, by a green pyroxene. Other minerals also occur in subordinate amount. It has been found in various places in Europe, and has recently been described as occurring in a Californian locality. A closely related hornblende-schist full of garnets is found also in Hanover, New Hampshire.

Glaucophane-schist is a variety in which ordinary hornblende is replaced by the soda-bearing species glaucophane, and for this reason the rock is colored blue instead of green. Various other minerals may be present, depending on the occurrence, such as quartz, epidote, pyroxene, chlorite, garnet, etc. Sometimes they are coarse grained and these other minerals may be seen, sometimes dense and appear as slaty blue or blue-gray rocks. Studies which have been made of them show that sometimes they have been produced by the metamorphism of sedimentary, sometimes of igneous, material. While comparatively rare they have been found widely distributed, in California, Brittany in France, the Alps, Island of Syra, Greece, Japan, Australia, etc.

Greenstone-schist in its relation to amphibolites has been already mentioned under chlorite-schist. As the use of the term "greenstone" has been vague, applying rather to color than to a determined mineral composition, many rocks which are hornblende-schists, rather than chlorite-schists, have been included under it.

Occurrence of Amphibolites. These form layers and masses in other metamorphic rocks, especially in gneisses and mica-schists, rather than extensive independent formations. They often occur in gneisses in long bands or veins in such a manner as to suggest that they are metamorphosed dikes of doleritic rock. In size the masses may vary within the widest bounds, from one foot to thousands in diameter. In some places, what they lack in size, they make up in frequency of occurrence. The manner in which they are interlaminated in places with other metamorphic rocks suggests that they may have been sometimes formed from intrusive sheets of igneous rock, and sometimes from interbedded sediments, but in general this can only be rendered certain by further chemical and microscopical investigation. Their occurrence as mantles around igneous masses has been already mentioned.

The amphibolites are extremely common rocks, in all metamorphic regions. Thus they are found commonly distributed in New England and New York State, and southward to Georgia; in Canada, the Lake Superior region, the Sierras, in England, Scotland, the Alps, etc.

Alteration. It has been already pointed out under chlorite-schists that the hornblende of these rocks may be changed into chlorite. In another form of alteration it may be turned into serpentine with other minerals, and thus give rise to serpentine rocks, whose character is described later. These changes take place in the upper belt of metamorphism, that of hydration and cementation, and are secondary to the processes which have produced the amphibolite from something else. They might thus be spoken of as tertiary changes.

By the ordinary process of weathering on the surface, these rocks change to masses of limonite, clay, calcite, etc., which form ferruginous soils.

MARBLE AND CARBONATE-SILICATE ROCKS.

Marble is the metamorphic condition of sedimentary rocks which are composed of carbonate of lime, $CaCO_3$, and which in their ordinary stratified form are known as limestone, chalk, etc. It is distinguished from them by its crystallization, coarser grain, compactness and purer colors. But just as we have ordinary limestones which contain only carbonate of lime, and dolomitic limestones which contain magnesian carbonate, $MgCO_3$, in variable quantity associated with the lime carbonate, so we have lime marbles and dolomite marbles. As this distinction is a purely chemical one which is rarely made, and indeed rarely can be made in ordinary and commercial usage, the rock is, therefore, called marble, without regard to whether it contains magnesia or not. But geologically, especially from the petrographical standpoint, there is an important difference between the two rocks in respect to the associated minerals they are apt to contain when impurities were present in them originally, and therefore they are treated separately in this work for reasons which will presently appear.

General Properties. Marble is a crystalline granular rock composed of grains of calcite; sometimes these are cemented by a fine deposit of calcite between them. The grain varies from very coarse to such fine compact material that individual grains cannot be distinguished; in the coarsest varieties, the cleavage surfaces of individuals may attain a breadth of half an inch or more, but this is unusual. The fracture surface of the finest-grained kinds has a soft, shimmering luster, while the appearance of coarser kinds is like that of loaf sugar. The normal color is white, like that of the best statuary marble, but the rock is usually more or less colored by various substances which act as a pigment, the principal ones being carbonaceous matter and the oxides of iron. It thus becomes gray, yellow, red or black, and while the color is sometimes uniform, it is more generally spotted, blotched, clouded or veined, producing that effect which is known as "marbled." The hardness is that of calcite, 3; the rock is thus readily scratched or cut by the knife, a ready means of distinction from quartzite or sandstone, which may resemble it. It is readily soluble in weak acids. Unless the grain is too fine, the good rhombohedral cleavage of the calcite grains can be easily seen with a lens. The chemical composition of a perfectly pure marble would be that of calcite, $CaO = 56$, $CO_2 = 44$ per cent, but there are usually small quantities of magnesia, alumina, iron and silica present, coming from traces of sand, clay, dolomite, etc., mixed with it; these may increase until the impure marbles are produced, which are described in a later paragraph.

Unlike most metamorphic rocks, marble, if pure, is very massive and shows no sign of schistose cleavage, even where its association with schists is such as to indicate that it must have been subjected to enormous pressure and shearing stresses. If impurities in the form of other minerals are present it may then assume cleavage, caused by their presence. The reason for this want of cleavage has caused much speculation; it is probably due to several causes, to the purity of the rock, to a rolling of the grains among themselves, but chiefly to a curious property which calcite possesses of permitting movement among its molecules, whereby new crystal forms are produced without destruction of its substance; this results in a complicated microscopic twinning, somewhat similar to that explained under feldspar. As a result of this the stresses are absorbed molecularly, instead of producing changes in the outward structure, as in most rocks.

Varieties of Marble. The varieties of marble from the technical point of view are chiefly those which are based on color. *Statuary marble* is the purest and whitest kind. *Architectural marbles* are those of the most uniform tones of color, while *ornamental marbles* are those distinguished by striking effects of varied colors, as mentioned above. In the trade, the term marble is used for any lime carbonate or dolomite rock which can be procured in large, firm blocks, and is susceptible of a high polish; under this definition many limestones are included. *Shell marble* is thus a hard, firm limestone in which a certain pattern is given by the presence of certain fossils, shells of brachiopods and remains of crinoid stems being the most common. The different yellow, red, and black marbles, most of them veined and clouded, of Italy, Greece, and the East have long been distinguished by a host of names.

Those varieties which depend on the presence of some mineral, additional to the calcite, are treated in the following section on carbonate-silicate rocks.

Occurrence of Marble. The great deposits of marble, from which the material used for structural purposes is taken, are the result of regional metamorphism and it is thus found in regions of metamorphic rocks associated with gneisses, schists, etc., in the form of interbedded masses, layers, or lenses. These vary in size within wide bounds, from a few feet to many miles in length. It forms immense interbedded layers, or masses, in the Laurentian rocks of Canada; it occurs in quantities in

Vermont, Massachusetts, Georgia and Tennessee, where it is extensively exploited, in Colorado and other places in the west. The marbles of Greece and Italy have attained celebrity from their use by the ancient Greeks and Romans in statuary and buildings. It is found in the Alps, Germany, and Scandinavia in Europe, and in various other places in the world. Marble is also produced from limestone (and chalk) by the contact action of intruded igneous rock. Although some very coarse-grained material may be formed in this way, it is usually quite limited in amount.

Lime Carbonate-Silicate Rocks. As described under the general properties of sedimentary rocks, all transitions occur between limestones and sandstones, between limestones and shales, and between the three combined. This means merely, that the original lime deposits may have had sand, clays, silt, and ferrugineous material in variable amounts, mixed with them. Chemically, it means that the carbonate of lime has silica, the oxides of aluminum and iron, and usually small amounts of other things, such as magnesia, potash, and soda mixed with it. Under the conditions of metamorphism the carbon dioxide, CO_2, is driven out, to be replaced by an equivalent amount of silica, SiO_2, and thus silicates of lime, of lime and alumina, of lime and iron, or mixtures of these, or combinations containing other elements as well, are formed. Also volatile substances, liquids and gases, such as water vapor furnishing hydroxyl, fluorine, boron, etc., emanations from magmas resting below or being intruded simultaneously with the crustal movements which give rise to the metamorphosing conditions, may enter the rock mass and thus, in adding new substances, produce additional mineral combinations. The amount of silica present may be sufficient to completely replace the carbon dioxide and the resulting rock is then composed entirely of silicates, or it may not be sufficient to accomplish this, and the mass then consists of a mixture of lime carbonate, calcite, mixed with silicates. Thus all transitions may be found from pure marble, through varieties containing bunches, masses, and individual crystals of some mineral, or minerals, into rocks completely made up of sometimes one silicate, but usually of a mixture of them. The whole affair is quite analogous to what has already been described as the effect of contact metamorphism of igneous rocks on impure limestones in a previous part of this book, and the chemical reactions which take place are the same as those there mentioned. The resulting rocks are also quite similar, with, however, one difference. In contact metamorphism the chief agency is heat, while pressure and shearing are either wanting, or are relatively of slight importance, but in regional metamorphism these are factors of great intensity. Thus the rocks of contact metamorphism are massive and with little or no schistose cleavage, while those produced by regional metamorphism may strikingly exhibit it; that cleavage is not always present is due to the reason given above under the description of marble.

Important minerals which thus occur in limestone are *pyroxenes* (especially wollastonite, $CaSiO_3$, and diopside, $CaMgSi_2O_6$); *garnets* (especially grossularite, $Ca_3Al_2(SiO_4)_3$); hornblendes (especially tremolite, $CaMg_3Si_4O_{12}$); *feldspar* (especially anorthite, $CaAl_2Si_2O_8$); *vesuvianite; epidote; fluorite,* etc. A whole host of minerals occurs, but many of them, such as graphite, magnetite, spinel, titanite, tourmaline, apatite, phlogopite, etc., come chiefly from the impurities in the original rock, which have been recrystallized.

It is clear from this, that, depending on mineral combination, a great variety of these lime carbonate-silicate rocks exist. but only a few of the most important types can be mentioned.

Wollastonite-rock. Marble not infrequently contains crystals of the pyroxene-like mineral, wollastonite, $CaSiO_3$, and this may increase until the rock is practically composed of it. It is apt to be accompanied by diopside, hornblende, etc. The rock is white, generally massive, and resembles marble, from which it is easily distinguished by its superior hardness. It occurs in California, the Black Forest, Brittany, etc.

Garnet-rock. This is a granular aggregate of grains of garnet, generally accompanied by various other minerals in smaller, variable amounts. If some calcite is yet present the garnets may show more or less crystal form; sometimes the calcite has been leached out and the rock is porous. Apt to be yellowish, to reddish brown, in color. Considerable magnetite is often present. New England, northern New York, Montana, Germany, Alps, etc.

Epidote-rock, or Epidosite. Composed chiefly of epidote with other minerals, quartz, garnet, etc. Sometimes massive granular, sometimes schistose. Greenish in color, especially of a yellow-green. Often very tough under the hammer. New England, Brazil, Germany, etc. Sometimes the ferromagnesian igneous rocks, basalt and dolerite, under proper metamorphic conditions, are converted into a rock consisting chiefly of epidote, instead of hornblende or chlorite as previously described, and of a yellowish green color. They may resemble the above, but can usually be distinguished by their mode of occurrence, geologic relations, greater uniformity, and often by the remains of special structures, such as the amygdaloidal. Instances occur in Pennsylvania, Virginia, etc.

Pyroxene-rock. In this case the rock consists chiefly of pyroxene, of which the variety diopside is prominent. Other minerals, quartz or calcite, etc., may occur. White, greenish, to dark green in color, massive or schistose. Is found in Massachusetts, northern New York, Germany, Bohemia, Sweden, etc. Under the head of metamorphic pyroxene rocks there may be mentioned in this connection jade, which, although extremely rare, is of great interest from its ethnological and artistic importance. *Jade* is a fine-grained, and usually compact, aggregate of grains and fibers of the soda-pyroxene, jadeite, $NaAlSi_2O_6$. It is sometimes snow-white, resembling marble, but usually greenish (or with a violet shade) to dark green. The greenish colors are also clouded, veined, or specked through the white. When polished it has a soft, somewhat greasy luster. The extraordinary toughness of the rock is one of its most marked characters and on this account it was greatly prized in the early history of mankind, before the discovery of metals, for the manufacture of weapons and implements, as shown by its distribution in these forms, and in unworked pieces over the world. It has long been greatly valued by the Chinese, who have devoted the most laborious work to fashioning it into objects for personal adornment and use. These objects, such as vases, bowls, etc., are often carved with wonderful skill and taste and are greatly prized for their artistic value. The rock is only known in place in upper Burma and in the Kuen-lun Mountains of Turkestan. Its origin is uncertain, but its chemical composition suggests that it may be a metamorphosed igneous rock of high soda content, such as nephelite-syenite. A green hornblende rock called *nephrite*, from Siberia and New Zealand, has similar properties and uses and is frequently mistaken for jade.

Cipolin is a marble full of mica, which may show transitions to calcareous mica-schist. Usually other minerals, sometimes in considerable variety, are also present.

Dolomite Marble, Magnesia-Silicate Rocks. As mentioned under dolomite limestones, the rock name does not necessarily mean that the substance composing it is pure dolomite, in the mineralogical sense. There is generally an excess of lime carbonate present, so that the composition is a mixture of dolomite, $MgCa(CO_3)_2$, and calcite, $CaCO_3$. Just as marble is related to ordinary limestone, so is dolomite marble to ordinary dolomite. In a practical way no distinction can be drawn between the two varieties of marble, except chemically. See dolomite under the rock minerals. Like ordinary marble, dolomite is one end of a series of metamorphic rocks, which, beginning with a pure carbonate, becomes a mixture of carbonates and silicates, and ends in pure silicate rocks. The causes and processes are identical with those described under marble, only in this case the presence of magnesia causes the formation of silicate minerals, in which this element is either the only metal, or a very important one. Thus in distinction to the lime carbonate-silicate series, this may be called the magnesian carbonate-silicate series. The magnesian silicates thus produced in the zone of constructive metamorphism may be anhydrous, or nearly so; on the rocks rising, by erosion or otherwise, into the zone of hydration, they may be secondarily converted in serpentine, $H_4Mg_3Si_2O_9$, or sometimes into talc, $H_2Mg_3(SiO_3)_4$. Thus these rocks are in many cases closely connected with the talc-schists previously described, while their relation to serpentine is mentioned under that rock. The more important magnesia silicates which take part in the series are olivine, enstatite, chrondrodite, diopside, tremolite, phlogopite, etc., and secondarily serpentine and talc, as stated above. Of the varied rocks formed by these mixtures, only a few of the most important can be mentioned.

Crystalline dolomites, or dolomitic marbles filled with variable mixtures of minerals, chrondrodite, phlogopite, pyroxenes, etc., with others, such as magnetite, spinel, apatite, graphite, etc., coming from original impurities, are found rather commonly in the metamorphic areas in the eastern United States and Canada, but have received no distinctive names, as rocks. They appear to have been formed sometimes by contact, sometimes by regional metamorphism, often by a combination of both.

Ophicalcite is a mixture of white calcite and green serpentine, the latter often in veins, spots, or clouded through the rock. A part of the "verde antique" marble of the ancients, used for ornamental purposes, appears to have been a variety of ophicalcite. It occurs in Canada, northern New York, and various places in Europe.

Soapstone and talcschist. Part of the rocks included under these names belong in this series: they have been already described under a previous section. *Listwänite,* which occurs in the Ural Mountains, and in Spain, is a mixture of magnesia carbonates (magnesite, $MgCO_3$, and dolomite), with talc, and with more or less quartz *Sagvandite,* from Norway, is a granular mixture of varieties of magnesite and enstatite ($MgSiO_3$) containing ferrous iron.

Amphibolites. Many of the hornblende-schists or amphibolites, previously described in a separate section, are the result of the transformation of impure limestones and dolomites into metamorphic rocks. This has been already discussed, but it should be again mentioned here, because the amphibolites, made in this way, form one of the most important members of the lime and magnesia series of carbonate-silicate rocks described above.

Occurrence of Minerals and Ores. The crystalline marbles and dolomites, in addition to the minerals mentioned above, not infrequently, owing to local causes, contain a great variety of others. Thus at Franklin, New Jersey, owing to the presence of zinc and manganese, a number of minerals containing these metals have been produced, forming useful ores. Ore-bodies are mostly developed in these rocks, however, by contact metamorphism, but in some cases the minerals developed by regional metamorphism are of such a character, and in such quantity, that they may be usefully exploited. Many of the famous mineral localities, specimens from which are commonly seen in collections, are in these rocks. The minerals thus found embedded as crystals in calcite and dolomite, are apt to have the angles between the faces more or less rounded, and to be veined with calcite in their cracks.

SERPENTINE.

General Properties. No close distinction between serpentine, as it has been described as a mineral, and serpentine as a rock can be made. As a mineral the chemically pure substance was considered, but serpentine as a rock is generally more or less impure from the presence of other minerals which are mixed with it. Serpentine rocks are generally compact, of a dull to waxy luster, and of a smooth to splintery fracture. If tolerably pure they are soft and can be cut by the knife, but they are sometimes saturated by deposited silica, which makes them much harder. The general color is green, characteristically a yellowish-green; but sometimes yellow, yellow-brown, reddish-brown, and dark green to black. On smooth surfaces the rock has a somewhat greasy feel, recalling talc-schists, from which it is, however, readily distinguished by its superior hardness. Talc leaves its mark on cloth, while serpentine does not. The yellow-green color resembles also that of epidote rocks, but here again the superior hardness of the epidote serves as a distinction.

Associated Minerals. Other minerals which may accompany the serpentine, and which may at times be seen in it, are remains of the magnesia silicates from which it has been formed, olivine, pyroxene, and hornblende. Metallic-looking specks or crystals of ores are common, magnetite, chromite, etc. In some varieties garnet occurs, chiefly pyrope, and that which is used for gems comes in large part from a serpentine in Bohemia. In the Ural Mountains serpentine is the source of platinum, and in other places of nickel ores. Serpentine is apt to be accompanied by other secondary minerals, by chlorite (sometimes the purple-red variety kämmererite containing chromium), by talc, and by magnesium carbonates, magnesite, $MgCO_3$, and breunnerite, $MgFeCO_3$, etc. Serpentine rocks are usually massive but sometimes schistose, serpentine-schist. Not infrequently they are seamed by veins of the finely fibrous variety of the mineral called chrysotile, which has the structure of asbestus and is often so called.

Chemical Composition. The chemical composition of serpentine rocks approaches that of the pure mineral, but generally differs somewhat on account of the other minerals present. This is seen in the appended analyses:

	SiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	FeO	NiO	Mg	CaO	H_2O	CO_2	XyO	Total.
I	40.4	1.9	0.3	2.8	4.3	0.5	36.0	0.7	10.7	1.4	0.6	99.6
II	36.6	1.0	0.3	7.3	0.4	0.3	40.3	0.1	13.4	—	0.4	100.1
III	38.6	1.3	0.5	5.6	2.2	0.1	39.1	0.9	11.3	0.5	0.2	100.3
IV	36.9	1.4	—	6.9	4.0	—	36.0	1.4	13.1	—	—	99.7
V	42.3	0.8	—	—	2.6	—	40.3	1.3	12.5	—	0.5	100.3
VI	44.1	—	—	—	—	—	43.0	—	12.9	—	—	100.0

I, Serpentine, dark-green, Rowe, Massachusetts; II, Serpentine, from pyroxenite dike, Mount Diablo, California; III, Serpentine, Iron Mountain, Oregon; IV, Serpentine, from hornblende-schist, Vosges Mountains, Germany; V, Serpentine, white, selected pure mineral, Brewsters, New York; VI, Theoretical composition of pure mineral, $H_4Mg_3Si_2O_9$.

The presence of small quantities of nickel and chrome oxides is a very common feature.

Origin. Serpentine rocks are secondary in nature, being formed when previously existent rocks, consisting wholly or chiefly of magnesian silicates, are exposed to the processes at work in the zone of hydration. Their origin may thus be twofold: they may be formed from igneous rocks, such as peridotite, dunite, etc.; or when amphibolites or hornblende-schists, which have been made from sediments in the zone of constructive metamorphism, are brought by erosion into the zone of hydration, they may be converted into serpentines. Thus the origin of the material may be igneous or sedimentary, but, whereas the igneous rocks pass directly into serpentine, the sedimentary ones first pass through an intermediate metamorphic stage (hornblende-schists, etc.), and are then converted. In this connection what has been said elsewhere concerning the alteration of the peridotites and allied rocks should be read. This also explains in part at least the origin of the chromium and nickel. No formula can be given for the recognition of which origin a serpentine has had; the geologic mode of occurrence and relation to other rock masses is often a help, while the presence of nickel and chromium, — substances to be expected in igneous, but not in sedimentary rocks, — if it can be shown, is very significant.

Occurrence. Serpentine is a common rock, and, while it rarely forms large masses or covers extensive areas, it is widely distributed over the world. In the form of layers, lenticular masses, etc., it is common in metamorphic regions from the alteration of both igneous and metamorphic rocks, and it thus occurs in eastern Canada, New England, New York, Pennsylvania, Maryland, California, Oregon, and other states; in southern England, Germany, the Alps and various other places. It also occurs in non-metamorphic sedimentary areas due to the conversion of igneous rocks which have penetrated the strata, as in places in Quebec, New Brunswick, New York state, etc.

Alteration, Uses. Serpentine shows great resistance to the action of the weathering agencies at the surface, but eventually breaks down into a mixture of carbonates and silica, mixed with ferruginous matter. The soils thus formed, on account of the lack of alkalies and lime, are extremely barren, and often little or no vegetation grows upon them.

On account of its beautiful coloring, serpentine has been largely quarried for use as an ornamental stone, being used for interior purposes much as highly colored marbles are. It is sometimes employed for the same objects for which soapstone is used; in many cases its softness is an objection to its employment. In some places the seams of fibrous chrysolite which it contains are mined for use as asbestus. Its value as a source of ores of nickel, chromium, etc., has been already commented upon, and is further mentioned under peridotites and allied rocks.

IRON OXIDE ROCKS.

Itabirite. This rock is composed chiefly of micaceous hematite and quartz. The micaceous hematite, or "specular iron ore" as it is often called, is in very thin tablets or leaves of irregular outline, while the quartz is in aggregates of grains. It much resembles mica-schist, and if one were to imagine the mica of such a schist replaced by a substance of mica-like thinness but with the metallic luster of polished iron, he would have a good idea of the appearance of this rock. Micaceous hematite is indeed of not infrequent occurrence in genuine mica-schists, and by its increase transition forms to itabirite are produced. Also, just as the relative quantities of quartz and mica vary in different layers of mica-schist, so do the micaceous hematite and quartz vary in itabirite; thus there are layers poor in quartz, and others quite rich in it, of very variable thickness. In addition to the mica, magnetite, pyrite, talc, garnet, and others may occur as perceptible accessory minerals. The rock is generally granular to fine granular; very schistose; of a dark color on the cross-fracture, and exhibits on the chief fracture the shining steel-like luster of the specular iron ore. Sometimes the amount of the iron mineral is so great as to practically conceal the quartz. Itabirite forms extensive areas in Brazil and on the Gold Coast of Africa, and in these places carries native gold. It also occurs in North and South Carolina, in Canada, Norway, Germany, etc. It has probably been formed by the metamorphism of sandstones and shales rich in deposited ferruginous matter, limonite, etc.

Jaspilite is a name given to somewhat similar rocks which consist of layers of red chert and hematite. They occur in the Lake Superior Region. See page 297.

Magnetite Rock. This is a compact to granular aggregate of grains of magnetite; dark-colored to black, and heavy. The properties are those described under the mineral. Hematite is very commonly mixed with it, and a variety of other minerals, such at ilmenite, pyrite, quartz, calcite, garnet, etc., according to the mode of occurrence. The origin of magnetite rock is various; thus it may occur as masses included in, or associated with, igneous rocks, and is then regarded as a differentiated phase of such rocks, as mentioned under them, and in this case the associated minerals vary with the kind of rock, as nephelite and augite, when with nephelite-syenite (Arkansas, Brazil, Sweden); olivine, pyroxene, lime-soda feldspar when with gabbros (Adirondacks, Sweden, Canada, Colorado, etc.). In other cases it occurs as a contact formation where igneous rocks have metamorphosed beds of limonite, siderite, etc. Finally it occurs in regional metamorphosed areas, in the form of layers and lenses, in the midst of gneisses and schists, and often associated with metamorphosed limestones and dolomites. It then often contains carbonates of lime and magnesia, as well as the more common of the silicate minerals described as associates of marble, such as garnet, pyroxene, hornblende, etc. It is probably due to the metamorphism of beds of impure limonite, clay-ironstone, etc. Deposits of magnetite rock occur in many places in the United States and Canada, in Scandinavia, Germany, the Ural Mountains, etc., and are of great importance as sources of iron ore. Those which are situated in genetic connection with igneous rocks are, however, generally useless on account of the presence of ilmenite, titanic iron ore, which prevents their being profitably smelted.

Emery. This is a granular rock of a dark-gray to black color, consisting mainly of grains of gray or bluish corundum, often mixed with magnetite, and associated with other minerals. It is sometimes quite schistose. It is easily told by its weight and excessive hardness (corundum = 9). It occurs, as layers of relatively small volume in the crystalline schists, in Asia Minor, Island of Naxos, Germany, Massachusetts, etc. Its use as an abrasive material, on account of the corundum it contains, is well known.

CHAPTER XII.

THE DETERMINATION OF ROCKS.

THE determination and classification of rocks presents itself as a problem, whose difficulty depends on what is sought to be done, and the means at command for carrying it out. It is obvious that the fine distinctions made by petrographers among rocks, especially the igneous ones, cannot be carried into ordinary practice, unless the same methods for the study of rocks — the use of the microscope on sections ground thin and chemical analyses — are employed which they use. This, of course, cannot be ordinarily done, and we are thus limited to the means of observation which have been used in this work, and to simple classifications and the limited number of kinds which they afford. This has already been commented upon, in discussing the classification of the igneous rocks, and need not be repeated.

Rock Characters used in Determination. The characters of rocks which may be used for their megascopic determination are of two kinds, *mineral* and *general*. By the mineral characters it is meant, that if the rock is composed wholly or in part of mineral grains, which are large enough to be distinctly seen with the eye or lens, and which may be, if necessary, handled and tested, then the determination may proceed along the line of a study of the minerals, their kinds, relative abundance, and relation to each other (rock-texture). In this case there is no essential difference between the microscopic and megascopic study of rocks; one can accomplish, in the main, on the fractured surface of a coarse rock, what the microscope does on the thin section of a compact one. The individual minerals may be studied and tested according to the methods given in Chapter V; if in the field, the simple tests of Table No. I may be used; if the conveniences of a laboratory are at hand, the more complete one, Table No. II can be employed. If it has been already determined, perhaps in the field, whether the rock is igneous, sedimentary, or metamorphic, its place can then be usually very quickly settled. Even if all the different kinds of minerals cannot be told, the determination of one or more will generally be of service.

The *general* characters are those which are resultant from the combination of mineral grains; they might be termed composite features of rocks. They include *color, structure,** *texture, fracture, hardness,* and *specific gravity.* Of these the specific gravity is of the least general applicability, because it requires a special apparatus to determine it. The reaction of the rock with acids is also at times extremely useful as a test, and may be added to the list. These general characters are so useful that they deserve some separate mention in regard to their employment in rock determination.

Color. The rock color is the general resultant of those of the combined mineral grains. Certain general conclusions may be drawn from the color of a rock; thus if it is pure white or nearly so, it is certain that compounds of iron are either wanting in it, or are only present in traces, and in general the rock is either a sandstone, quartzite, limestone-marble, gypsum, or a nearly feldspathic igneous rock, such as anorthosite, aplite, syenite, or felsite. Red, brown, and green colors indicate the presence of iron compounds; black or stone gray may also, but in a sedimentary rock, these colors may indicate carbonaceous material.

Structure. If the rock has a pronounced structure of some kind, it may be of great assistance in determining the general class to which it belongs, and this may be of especial assistance if the geological relations of the rock

---

* The difference between the use of "structure" and "texture" has been already explained, p. 158.

mass cannot be determined. Thus if a rock mass possesses a pronounced columnar, or a highly vesicular, or an amygdaloidal structure, it is almost certainly of igneous origin; if a laminated or banded structure, it is probably sedimentary; but this cannot be definitely relied on, because igneous rocks, especially lavas, may assume a banded structure by flowage, while metamorphic rocks may acquire it by shearing movement. The oölitic structure indicates a sedimentary rock. In general, structure must be considered in connection with texture and other properties.

Texture. Certain textures are of definite assistance in determining the family to which a rock belongs. Thus the glassy texture is definite proof that the rock is of igneous origin; a porphyritic texture shows the same thing, especially if the phenocrysts are well crystallized, and of quartz, or feldspar, or both. Metamorphic rocks also contain at times well crystallized minerals, which are similar to phenocrysts, as, for instance, garnet and staurolite, but in general they also possess at the same time a well foliated structure, which helps to distinguish them. Sedimentary rocks do not exhibit this texture. The mere contrast in color of a few dark mineral grains among many lighter ones must not be mistaken for a porphyritic texture. In general, a hard, firm, highly crystalline texture, alike in appearances in all directions through the rock, is indicative of an igneous origin; but there are many exceptions to this rule, as shown in various marbles and quartzites. If a rock has a highly crystalline texture, and at the same time a foliated structure, it is probably metamorphic.

Hardness. This character, which can readily be tested in a rough way in the field, is very useful in distinguishing between certain classes of rocks. Thus very fine-grained compact sandstones (or quartzites), limestones, and dense igneous rocks often look much alike in specimens. A simple test of hardness with the knife-point will at once distinguish between the limestones (carbonate rocks, soft) and the others mentioned (silicate, or silica rocks, hard). If the rock is not very firm, care must be taken not to confuse the mere breaking down or crushing of the rock fabric with actual scratching of its component minerals. If the rock itself is used to scratch with, care must also be taken to test a number of corners, or edges, so that some single grain, harder than the average, may not produce a false impression of the average hardness.

Fracture. This is of less importance than the foregoing characters, but yet in some ways is of value. Most rocks which are firm and solid enough to have a distinct fracture exhibit a more or less rough, hackly one. Those which are fine-grained, or dense and compact, and which contain a large amount of silica, or are wholly composed of it, such as felsites, quartzites, flint, etc., possess a more or less distinct conchoidal fracture, and the surface may be splintery. Some dense limestones also have a splintery fracture, and may even approach the conchoidal. Natural glasses, such as compact obsidian, have a beautiful conchoidal fracture.

Specific Gravity. This property is of much greater value in the determination of minerals than of rocks. It cannot of course be used in the field, as it requires definite apparatus to determine it, as described in Chapter III, under minerals; nevertheless, even in the field, a rough distinction may be made between light and heavy rocks, by weighing them in the hand. Rocks that are dark-colored and very heavy, in general, are composed largely, or chiefly, of iron-bearing minerals, and are apt to be of igneous, or of metamorphic origin.

Treatment with Acid. This is particularly useful in distinguishing the carbonate from the silicate rocks. The method of treatment has been fully described in Chapter V, and need not be repeated here. If necessary almost any acid may be used, such as vinegar (acetic acid), or lemon juice. For field use a few crystals of citric acid powdered up may be conveniently carried, and dissolved, when needed, in a little water; the test for effervescence can thus be readily made. The test for gelatinization, as also described in Chapter V, is also very useful in determining the nephelite syenites from other syenites and from granites, and also its effusive representative, the phonolite variety from the other felsites. It should be remembered that olivine, which, however, chiefly occurs in the dark ferromagnesian rocks, gabbros, peridotites and basalts, also gives this gelatinization test.

Determination in the Field. The best method of determining the family to which a rock belongs, that is, whether it is sedimentary, igneous, or metamorphic, is to study its characters in the place in which it occurs, and its relation to other rock masses. For these features, and the larger ones of its structure, may be very apparent in the field, while a simple hand-specimen may entirely fail to show them. The structure of a granite-gneiss, for instance, may be very clear on the surface of a field exposure, and be quite inappreciable in a small specimen. It is not necessary to give here the characters and relations by which the class may be determined; this is geological rather than petrographical, and has been sufficiently commented upon in Chapters VI, VIII and X. If the family has been determined in the field, and the rock is coarse-textured, so that the mineral grains can be seen, and if necessary handled, Table I (p. 124) of Chapter V may be used for their identification, and by then referring to the classification of the appropriate family, its place in general can be readily determined.

Table for Rock Determination. Appended to this chapter is a table which may be used for the determination of the more important kinds of rocks. It is based essentially on the one given by Geikie, in his Textbook of Geology, which has, however, been considerably modified, and extended to meet the needs of this work. As the tests which it demands are very simple, consisting for the most part of those relating to hardness and effervescence with acid, it may be readily used, even in the field. It must be remembered, however, that a table of this nature can be only quite general in character, and applicable to rocks of well-defined types. Rock kinds grade into one another in so many ways, as has been described in a number of places in this work, that not only the student, but even the experienced geologist, will sometimes be puzzled as to the proper designation a particular type should receive. But if this fact is borne in mind, it is believed the table will prove useful in aiding one to classify the common rocks.

TABLE FOR DETERMINING THE COMMON ROCKS.

The newly fractured surface of the unaltered rock shows one of the following cases:

a. It is wholly or partly glassy. See **A** beyond.

b. Not glassy; of a dull, even appearance or stony; without particular texture, or so compact that the individual grains cannot be seen or recognized. See **B.**

c. Distinctly grained and crystalline; the grains can be seen and determined. See **C.**

d. Has a distinctly foliated or gneissoid structure. See **D.**

e. Has a clearly fragmental composition. See **E.**

A. *Wholly or partly glassy.*

1. Wholly of glass; solid; strong vitreous luster. *Obsidian*, p. 262.

2. Wholly of glass; solid; resinous or dull pitchy luster. *Pitchstone*, p. 265 (Obsidian and pitchstone may contain spherulites.)

3. Wholly of glass, but cellular or froth-like. *Pumice*, p. 266.

4. Of glass, but enamel-like, and composed of small, concentric spheroids. *Perlite*, p. 265.

5. Partly of glass and partly of distinct, embedded crystals. *Vitrophyre*, p. 267.

(The above forms are generally associated with, or pass into, felsite lavas.)

6. Glass associated with, or passing into, basalt; rare. *Tachylite*, p. 268.

B. *Compact, close-grained, and dull or stony; not glassy.*

a. Very soft; can be scratched with the finger-nail.

1. Has a strong earthy or clay odor when breathed upon; rubbed strongly between the fingers has ultimately a smooth, greasy feeling; does not effervesce with acids. Various colors. *Clay*, p. 327.

2. Friable; crumbling; soils the fingers; little or no clay odor; lively effervescence with acids; color white or light yellowish, etc. *Chalk*, p. 310 or perhaps *marl*, p. 313. (Marl may give a good clay odor.)

TABLE FOR DETERMINING THE COMMON ROCKS
Continued.

3. General characters as in 2, but does not effervesce with acids. *Diatomaceous earth*, p. 298.

4. Harder, more compact than 1, 2, and 3. No clay odor; does not effervesce; composed of a mineral with a good cleavage; sometimes fibrous; occurs in beds or veins. *Gypsum*, p. 293.

5. White to green, or gray; does not effervesce; no clay odor; mass has a soft, greasy feel; is often foliated or shows a micaceous cleavage; folia inelastic; marks cloth. *Talc-rock*, p. 374.

b. Not scratched by the nail, but easily scratched or cut with the knife.

1. Composed of excessively fine, almost imperceptible particles; dull, even appearance; gives clay odor when breathed on; no effervescence or but feeble; has a laminated or stratified structure and usually breaks easily into chippy flakes; generally gray, but often red, yellow, brown, bluish, or black. *Shale*, p. 327.

2. No clay odor, or but feeble; brisk effervescence with acid; white streak; commonly gray; sometimes white to brown or black. *Limestone*, p. 304.

3. As in 2, but feeble effervescence in acid, which becomes brisk when the acid is heated; generally white, yellowish or pale brown. *Dolomite*, p. 307.

4. Pale to dark green or black, sometimes reddish; soapy or greasy feel; translucent on thin edges; waxy or oily appearing; subconchoidal or splintery fracture; no effervescence. *Serpentine*, p. 392.

c. Not scratched or cut with the knife; scratches glass; does not effervesce with acid.

1. Various colors, white to red or purple, brown to dark gray; often gives a clay odor; frequently shows banded flow structure. *Felsite*, p. 248.

2. Very hard; any corner or angle scratches feldspar; no clay odor; scratches steel readily; light colors to brown or black; pronounced conchoidal fracture; glimmering horny appearance. A siliceous rock; either *flint*, p. 297, or perhaps the rhyolite variety of *felsite*, p. 249.

TABLE FOR DETERMINING THE COMMON ROCKS
Continued.

3. Not so hard as 1 and 2. Does not scratch feldspar; color black, very dark gray or green; is heavy; sometimes shows a cellular or slaggy structure; sometimes contains amygdules. *Basalt,* p. 254.

C. *Distinctly grained and crystalline; grains wholly or partly determinable.*

a. Is easily scratched with the knife.

1. Effervesces briskly with acid. *Limestone* p. 304, or more probably *marble,* p. 384.

2. Effervesces briskly only when the powdered rock is treated with hot acid. *Dolomite marble,* p. 390.

3. Does not effervesce; probably granular crystalline. *Gypsum,* p. 293, or *anhydrite,* p. 295.

4. Soluble, with distinct saline taste. *Rock-salt,* p. 295.

b. Hard; cannot be scratched with the knife, or scratches with difficulty. Silicate rocks, two cases arise, *x* and *y.*

x. It is composed of grains of approximately equal size; i.e., it is *even-granular,* like common granite. See **X.**

y. It is composed of larger, distinct crystals embedded in a finer-grained groundmass; i.e., it is a *porphyry.* See **Y.**

X. *An even-granular, massive, silicate rock.* See p. 155.

1. Mainly or wholly composed of quartz and feldspar. *Granite,* p. 205. See also *aplite,* p. 214.

2. Mainly or wholly composed of feldspar without quartz. *Syenite,* p. 218. See also *nephelite syenite,* p. 221 and *anorthosite,* p. 224.

3. Composed of feldspar and a dark ferromagnesian mineral; the latter equals or exceeds the feldspar; *a,* the dark mineral is mostly or wholly hornblende. *Diorite,* p. 226; *b,* the dark mineral is mostly or wholly pyroxene. *Gabbro,* p. 229; *c,* the dark mineral is indeterminable. *Dolerite,* p. 235.

4. Composed entirely, or almost entirely, of ferromagnesian minerals; generally heavy and dark green to black (sometimes yellowish, *dunite*). *Peridotite, pyroxenite,* etc., see p. 238.

TABLE FOR DETERMINING THE COMMON ROCKS

Continued.

5. Composed of grains of quartz; scratches glass or feldspar readily. *Sandstone,* p. 323, or *quartzite* p. 366.

6. Much less commonly than the above, massive silicate rocks produced by metamorphism may occur in this division. There are a number of different varieties, depending on the particular mineral, or minerals. *Epidote-rock, garnet-rock,* etc., would be examples. See *contact-metamorphism,* pp. 180, 186, and *carbonate-silicate* rocks, p. 384.

Y. *A porphyry* (see p. 156), *composed of phenocrysts and a groundmass.*

1. Phenocrysts of quartz and feldspar and, perhaps, of a ferromagnesian mineral in a groundmass of the same. *Granite-porphyry,* p. 243.

2. Phenocrysts of feldspar (and often of a ferromagnesian mineral) in groundmass of predominant feldspar. *Syenite-porphyry,* p. 243.

3. Phenocrysts of ferromagnesian minerals, or feldspar, or both, in a groundmass of feldspar and ferromagnesian minerals; feldspar phenocrysts frequently striated. *Diorite-porphyry,* p. 244.

4. Phenocrysts of quartz, or feldspar, or both, and sometimes of ferromagnesian minerals, in a predominant groundmass of light color and dense feldspathic aspect. *Felsite-porphyry,* p. 251.

5. Phenocrysts of feldspar, or of a ferromagnesian mineral, or both, in a dense, dark to black, and heavy groundmass. *Basalt-porphyry,* p. 254.

D. *It has a distinctly foliated, gneissoid, or slaty structure.*

1. It contains feldspar, and generally quartz, with mica (sometimes hornblende). *Gneiss,* p. 351.

2. It consists mainly or largely of mica; often considerable quartz is present, but feldspar is absent, or indeterminable. Frequently contains crystals of dark red to black garnet, more rarely staurolite, cyanite, etc. *Mica-schist,* p. 361.

3. Medium green, dark green or black; consists mostly of a felted or matted mass of small, to very fine or microscopic, bladed, or needle-like crystals arranged mostly, in one general direction, which promotes the schistose cleavage. Other minerals, such as garnet, may be present. *Hornblende-schist* or *amphibolite* (p. 379).

TABLE FOR DETERMINING THE COMMON ROCKS
Continued.

4. Very compact, or dense and fissile, splitting easily into thin, more or less tough, ringing slabs; usually dark gray, or green to black, but sometimes showing other colors. *Slate*, p. 369. (Sometimes contains large crystals of staurolite, andalusite, etc.)

5. Very fissile, but soft to the feel; laminæ not tough, but often brittle or crumbling; pronounced silky luster on the cleavage face. *Phyllite*, p. 372.

6. Soft, greasy feel; marks cloth; easily scratched with the finger-nail; usually whitish to light gray, or green. *Talc-schist*, p. 374.

7. Smooth feel; soft; green to dark green; glimmering luster. *Chlorite-schist*, p. 376.

E. *Has a clearly fragmental composition; is seen to be composed of fragments or pebbles of other rocks, or of smaller angular or rounded mineral fragments; if the latter, frequently shows evidences of stratification.*

1. The pebbles range from the size of a pea up and are rounded; quartz ones are common; they are embedded in more or less of a cement. *Conglomerate*, p. 320.

2. The pebbles are angular in shape. *Breccia*, p. 321.

3. Composed of various-sized angular fragments of volcanic rocks, such as felsite and felsite porphyry, of bits of pumice, or cellular lava, or of rounded, vesicular, volcanic bombs, etc., mixed with fine compacted material (volcanic ash). *Volcanic tuff* and *breccia*, p. 272.

4. Composed of more or less angular, but sometimes rounded grains, in size from that of a pea down; the grains are mostly, or wholly, composed of quartz, and scratch feldspar. Generally some cement is present, which, if the rock is light colored, is apt to effervesce with acid (lime carbonate); if red or brown does not. *Sandstone*, p. 323.

5. As in 4 but more or less feldspar is also present among the quartz grains. *Arkose*, p. 326.

INDEX

Actinolite, **61, 63**.
Adinole, 188.
Adobe, 331.
Aegirite, 55, 58.
Aeolian rocks, 275.
Albite, 34.
Alkalic feldspar, 34, 35.
Alumina, test for, 117.
Amphibole, 60.
" determination of, 66.
Amphibolite, 379, 391.
Amygdaloidal structure, 159
Amygdaloid, basalt, 256.
Analcite, 103.
Andalusite, 76.
Andesite, 250.
Anhydrite, mineral, **113**.
Anhydrite, rock, 295.
Anorthosite, 224.
Anorthite, 34.
Anthracite, 319.
Apatite, 95.
Aplite, 214.
Arfvedsonite, **61, 63**.
Argillite, 369.
Arkose, 326.
Aschistic rocks, 169.
Ashes, volcanic, 141.
Associations of minerals, **29**.
Augite, 55, 57.
Augitophyre, 257.
Average rock, composition, **18**.

Basalt, basalt-porphyry, **254**.
" amygdaloid, 256.
" quartz, 256.
Bathylith, 139.
Bauxite, 97.
Biotite, 50, 51.
Bituminous coal, 318.
Black-band ore, 302.
Bog iron ore, 301.
Bombs, volcanic, **141**.
Border zones in igneous rocks, 165.
Border zones, origin of, 170.
Boss, 138.
Bostonite, 254.
Breccia, friction, 322.
" sedimentary, 321.
" volcanic, 140, 272.
" " origin, 269.
Brown coal, 317.
Brownstone, 326.
Breunerite, 110.
Buhrstone, 368.

Calcite, 105.
Calcium, test for, **119**.
Calcareous tufa, 312.
Camptonite, 257.
Cancrinite, 48.
Carbonates, test for, **115**.
Cementation, zone of, **338**.
Chalcedony, 86.
Chalk, 310.
Chemical elements, **18**.
Chert, 297.
Chlorine, test for, **121**.
Chlorite, 98.
Chlorite-schist, 376.
Chloritoid, 54.
Chondrodite, 82.
Chrysotile, 101.
Cipolin, 390.
Classification, general, 6.
" fragmental volcanic rocks, 271.
Classification, glassy rocks, 261.
" igneous rocks, 191, 194, 203.
Classification, igneous rocks, table, 195.
Classification, metamorphic rocks, 348.
Classification, stratified rocks, 290.

Clay, 96, 327, 278, 280.
Clay ironstone, 301.
Cleavage of minerals, 26.
" " " effect of, 28.
Coal, 315.
" hard, 319.
" soft, 318.
Color of minerals, 23.
" " rocks, 399.
" " sedimentary rocks, 286.
Columnar structure, 162.
Comagmatic regions, 174.
Complementary dikes, 167.
Conglomerate, sedimentary, 320.
" volcanic, 322.
Consanguinity of rocks, 173.
Contact metamorphism, 180.
" " effect on limestone, 187.
Contact metamorphism, effect on sandstone, 186.
Contact metamorphism, effect on shale, slate, 188.
Contact metamorphism, endomorphic, 181.
Contact metamorphism, exomorphic, 183.
Contact metamorphism, modes of occurrence, 185.
Contact metamorphism, pneumatolytic, 189.
Contact metamorphism, ore bodies, 190.
Coquina, 311.
Cortlandtite, 238.
Corundum, 86.
Corundum-syenite, 226.
Crystals, defined, 21.
" form in rocks, 22.
" twinning of, 36.
Cyanite, 78.

Dacite, 250.
Decay of rocks, 276.
Determination of minerals, 114.
" " " tables, 122.
Determination of rocks, 396.
" " " table, 404.
Diabase, 235.
Diaschistic rocks, 169.
Diatomaceous earth, 298.
Differentiation, 164, 169.
Dikes, 134.
" complementary, 167.
Diopside, 55, 57.
Diorite, 226.
" rock relations, 229.
Diorite-porphyry, 244.
Dolerite, 235.
" use of word, 198.
" alteration of, 237.
Dolerite-porphyry, 244.
Dolomite, mineral, 108.
Dolomite, rock, 307.
" " origin, 308.
Dolomite-marble, 390.
Dunite, 238, 240.

Earth's crust, composition, 17.
" interior, state of, 14.
Eclogite, 382.
Elements, geologically important, 18.
Emery, 397.
Epidosite, 389.
Epidote, 73.
Eutaxitic Structure, 164.
Exotic mineral colors, 24.
Extrusive igneous rocks, 139.

Feldspars, 34.
" alteration of, 44.
" cleavage of, 40.
" color of, 41.
" crystal form of, 35.
" determination of, 46.
" twinning of, 36.
Feldspathoid minerals, 47.
Felsite, felsite-porphyry, 248.
" sheared, 373.
" varieties of, 249.
Ferromagnesian minerals, 146.
Field classification, 6.
Flint, 86, 296, 297.
Fluorine, test for, 121, 81.
Fracture of minerals, 29.
" conchoidal, 29.
" of rocks, 401.
Fragmental volcanics, 269.
Freestone, 325.

Gabbro, 229.
" alteration of, 232.
" iron ores in, 234.
Garnets, 70.
Garnet-rock, 389.
Gelatinization test, 115.
Geyserite, 296, 298.
Glassy rocks, 260.
" " alteration of, 269.
" " classification, 261.
Glaucophane, 64.
Glaucophane-schist, 383.
Gneiss, 351.
" field study of, 358.
" inclusions in, 356.
" texture of, 353.
" varieties of, 355.
Granite, 205.
" complementary dikes of, 214.
" contact of, 215.
" graphic, 212.
" orbicular, 211.
" pegmatites in, 212.
" porphyritic, 207.
" weathering of, 216.
Granite-porphyry, 243.
Granulite, 360.
Gravel, 278, 279.
Graywackĕ, 326.
Greenstone, 229, 377.
Greenstone-schist, 377, 383.
Greensand-marl, 325.
Grit, 325.
Ground mass defined, 156.
Gruss, 216.
Gypsum, mineral, 111.
Gypsum, rock, 293.

Halite, 113, 295.
Hammer, geological, 11.
" trimming, 12.
Hardness of minerals, 30.
" " rocks, 400.
Hauynite, 48.
Hematite, 91, 302.
Heulandite, 104.
Hornblendes, 60.
Hornblende-schist, 379.
Hornblendite, 238.
Hornfels, 188.
Hornstone, 188, 297.
Hydromica-schist, 373.
Hypersthene, 55, 57.

Ice, 20.
Igneous rocks, 132, 205.
" " consanguinity of, 173.
Igneous rocks, classification of, 191, 194, 203.
Igneous rocks, crystallization in, 146.
Igneous rocks, dense types, 247.
" " general characters, 132, 141.
Igneous rocks, inclusions in, 163.
" " jointing of, 161.
" " minerals of, 145.
" " occurrence of, 134.
" " origin of, 164.
" " petrology of, 132.
" " post intrusive work of, 174.
Igneous rocks, structure of, 158.
" " textures of, 150, 154.
Igneous rocks, variation of minerals in, 142.
Ilmenite, 90.
Inclusions in granite, 213.
" " gneiss, 356.
" " igneous rocks, 163.
Injection of schists, 345.
Intrusive sheets, 135.
Infusorial earth, 298.
Iron ores, 88, 299, 395.
Iron oxide rocks, 395.
Iron, test for, 118.
Itabirite, 395.

Jadeite, 389.
Jade, 389.
Jasper, 86, 297.
Jaspilite, 297, 396.
Jet, 319.
Jointing, 161.
" in granite, 210.

Kämmererite, 99, 393.
Kaolin, 96.
" from feldspar, 44.
Kimberlite, 242.

Labradorite, 35 (rock, 224).
Laccoliths, 136.
  " zoned, 166.
Lamprophyre, defined, 168.
Lamprophyres, 257.
Lapilli, volcanic, 141.
Laterite, 332.
Lava flows, 139.
Lepidomelane, 52.
Lepidolite, 52.
Leucocratic rocks, 167.
Leucophyre, 251.
Leucite, 49.
  " rocks, 259.
Lignite, 317.
Lime-carbonate-silicate rocks, 387.
Limestone, 303.
  " öolitic, 309.
Lime, test for, 119.
Limonite, 93, 301.
Listwänite, 375, 391.
Lithographic stone, 306.
Lithology defined, 2.
Lithophysae, 264.
Loam, 332.
Loess, 330.
Lydianite, 297.

Magmas, 134.
  " composition of, 141.
  " variations in, 142.
Magnesia-silicate rocks, 390.
Magnesite, 110.
Magnesium, test for, 119.
Magnetite, mineral, 89.
Magnetite-rock, 396.
Marble, 384.
Marble, onyx, 313.
Marl, 313.
  " *greensand*, 325.
Megascopic, defined, 7.
Melanocratic rocks, 168.
Melaphyre, 255.
Metadiorite, 229.
Metamorphic rocks, 333.
  " " age of, 346.
  " " classification of, 348.
Metamorphic rocks, composition of, 344.
Metamorphic rocks, injection of, 345.
Metamorphic rocks, minerals of, 339.
Metamorphic rocks, occurrence of, 346.
Metamorphic rocks, older structures in, 343.
Metamorphic rocks, origin of, 333.
Metamorphic rocks, textures of, 340.
Metamorphism, 333.
  " agents of, 335.
  " constructive, 338.
  " effect of depth, 337.
  " " " heat, 336.
  " " " liquids, 337.
Miarolitic structure, 159.
Micas, 50.
Mica-schist, 361.
Mica-trap, 257, 215.
Microcline, 36.
Microscopical petrography, 7.
Minerals, associations of, 29.
  " cleavage of, 26.
  " color of, 23.
  " exotic color of, 24.
  " defined, 21.
  " determination of, 114.
  " fracture of, 29.
  " hardness of, 30.
  " specific gravity of, 31.
  " streak of, 25.
Mineralizers, 149.
Minette, 237, 257.
Muscovite, 50, 51.

Natrolite, 103.
Necks, volcanic, 138.
Nephelite, 47.
Nephelite-syenite, 221.
Nephrite, 390.
Norite, 229.
Noselite, 48.
Novaculite, 297.

Obsidian, 262.
Occurrence of igneous rocks, 134.
Ocher, 328.
Olivine, 67.
  " nodules, 258.
  " rock, 238, 240, 390.
Onyx marble, 313.

Oölite, iron, 303.
" limestone, 309.
" siliceous, 368.
Opal, 86.
Ophicalcite, 391.
Order of crystallization, 146.
Ore bodies, 190, 391.
" " formation of, 170.
Origin of igneous rocks, 164.
" " metamorphic rocks, 333.
Orthoclase, 34.
Oxides, important, 20.

Paragonite, 51.
Peat, 316.
Pebbles, 279.
Pegmatite dikes, 175.
" " origin, 178.
Peridotite, 238.
" ores in, 241.
" relation to gabbro, 240.
Perlite, 265.
Petrographic provinces, 173.
Petrography defined, 2.
" microscopical, 7.
Petrology defined, 1, 2.
" history of, 4.
" of igneous rocks, 132.
Phenocrysts, 156, 245.
" pseudo, 342.
Phlogopite, 52.
Phonolite, 250.
Phosphate rock, 314.
Phosphoric acid, test for, 122.
Phosphorite, 314.
Phyllite, 372.
Pitchstone, 265.
Plagioclase feldspar, 34, 35.
Poikilitic texture, 239.
Porphyroid, 373.
Porphyry, 156, 242.
" *basalt*, 254.
" classification of, 195.
" *diorite*, 244.
" *dolerite*, 244.
" *felsite*, 251.
" *granite*, 243.
" *labradorite*, 257.
" *syenite*, 243.
Post-intrusive processes, 174.
Potash, test for, 120.
Pudding-stone, 321.
Pumice, 266.
Pyrite, 94.
Pyroxene, 55, 57.
" alteration of, 58.
" determination of, 60.
Pyroxene-rock, 389.
Pyroxenite, 238.

Quantitative classification, 203.
Quartz, 83.
Quartzite, 366.
" *oolitic*, 368.

Rhyolite, 250.
Rock salt, 113, 295.
Rocks defined, 3.
" determination of, 398.
" general classification of, 6
" table to determine, 405.

Sagvandite, 391.
Salic defined, 146.
Sand, 278, 280.
Sandstone, 323.
Scale of hardness, 30.
Schist, talc, 374.
" *mica*, 361.
" *hornblende*, 379.
" *hydro-mica*, 373.
" *greenstone*, 377.
" *glaucophane*, 383.
" *chlorite*, 376.
Schistose texture, 340.
Schlieren, 164.
Schorl, 78.
Scoria, 266.
Selenite, 111.
Sericite, 54.
Serpentine, 100.
Serpentine, rock, 392.
Shale, 327.
" *alum*, 329.
Siderite, 110, 301.
Silica, test for, 115.
Sillimanite, 78.
Silt, 278, 280.
Sinter, calcareous, 313.
" *siliceous*, 298.
Slate, 369.
" cleavage of, 371.
Soapstone, 378, 391.
Soda, test for, 119.
Sodalite, 48.

Soil, formation of, 276.
" gradation of, 278.
" movement of, 277.
Specific gravity of minerals, 30.
" " " rocks, 401.
" " table of, 31.
Specular iron ore, 91.
Spherulites, 264.
Spinel, 90.
Staurolite, 76.
Steatite, 378.
Stilbite, 103.
Stocks, 138.
Stratified rocks, 275, 293.
" " chemical origin of, 287.
Stratified rocks, classification of, 290.
Stratified rocks, color of, 286.
" " minerals of, 290.
" " origin of, 275.
" " structures of, 282.
" " texture of, 284.
Streak of minerals, 25.
Structures of igneous rocks, 158.
" " metamorphic rocks, 340.
Structures of stratified rocks, 282.
Sulphuric acid, test for, 121.
Syenite, 218.
" *common*, 219.
" *corundum*, 226.
" *nephelite*, 221.
Syenite-porphyry, 243.

Table determining rocks, 404.
" " minerals, 122.
Talc, 102.
Talc-schist, 374, 391.
Test for alumina, 117.
" " calcium, 119.
" " carbonates, 115.
" " chlorine, 121.
" " fluorine, 121, 81.
" " gelatinization, 115.
" " iron, 118.
" " lime, 119.
" " magnesium, 119.
" " phosphoric acid, 122.
" " potash, 120.
" " silicates, 115.
" " sodium, 119.
Test for sulphuric acid, 121.
" " water, 120.
Texture, augen, 343.
" even-granular, 155.
" factors influencing, 151.
" foliated, 341.
" igneous rock, 150, 151, 154.
Texture, lenticular, 341.
" metamorphic rock, 340.
" poikilitic, 239.
" porphyritic, 156.
" pseudo-porphyritic, 342.
" relation to occurrence 153.
Texture, schistose, 341.
" slaty, 342.
Thin sections, 8.
Tinguaite, 222, 254.
Topaz, 81.
Tourmaline, 78.
Trachyte, 250.
Trap, 257.
Travertine, 312.
Tremolite, 61, 63.
Tripolite, 298.
Troctolite, 230.
Tufa, calcareous, 312.
Tuff, volcanic, 140, 272.
" " origin of, 269.
Twinning of crystals, 36.
" " multiple, 38.
" use of, 46.

Uralite, 66.

Variation of minerals, 142.
" diagram of, 145.
Vesicular structure, 158.
Vesuvianite, 75.
Vitrophyre, 267.
Volcanic tuff, 272.
" *breccia*, 272.

Wacké, 259.
Water, test for, 120.
Weathering, belt of, 337.
" of rocks, 276.
Wollastonite-rock, 388.

Zeolites, 103.
Zinnwaldite, 52.
Zoisite, 74.

THIS BOOK IS DUE ON THE LAST DATE
STAMPED BELOW

AN INITIAL FINE OF 25 CENTS

WILL BE ASSESSED FOR FAILURE TO RETURN THIS BOOK ON THE DATE DUE. THE PENALTY WILL INCREASE TO 50 CENTS ON THE FOURTH DAY AND TO $1.00 ON THE SEVENTH DAY OVERDUE.

ENGINEERING LIBRARY

OCT 13 1946	642-3339
OCT 30 1946	
NOV 12 1946	
OCT 22 1947	
NOV 26 1947	

10m-7,'44(1064s)

995702 QE431
P68

Engineering
Library

THE UNIVERSITY OF CALIFORNIA LIBRARY