CHAPTER II

ROCKS, THEIR GENERAL CHARACTERS, MODE OF OCCURRENCE, AND ORIGIN

Introduction. — Knowledge of rocks — kinds, their mineral composition and general properties, structures and textures, mode of occurrence, etc., — especially the important and more commonly occurring varieties of igneous, sedimentary, and metamorphic ones, is of fundamental importance to the engineer. Among the more important reasons why the engineer should possess a good knowledge of the different kinds of rocks may be mentioned the following: (1) Rocks differ greatly in their value for building purposes; (2) they vary markedly in their weathering qualities — resistance to atmospheric agents; (3) they vary in hardness, which materially affects the rate of drilling them and necessarily the cost; (4) they differ widely in structure, a factor which has to be considered in connection with tunneling, quarrying operations, stability of rock cuts, dam foundations, reservoir sites, value for the various uses to which they are put, etc.

Definition of a rock. — Broadly speaking, a rock in the geological sense is the material that forms an essential part of the earth's solid crust, and includes loose incoherent masses, such as a bed of sand, gravel, clay, or volcanic ash, as well as the very firm, hard, and solid masses of granite, sandstone, limestone, etc. Most rocks are aggregates of one or more minerals, but some are composed entirely of glassy matter, or of a mixture of glass and minerals. When consisting entirely of mineral aggregates, a rock may be *simple* if composed of a single mineral, such as pure marble made up of calcite, or pure quartzite of quartz; or *compound* if composed of several minerals, such as common granite which is made up of a mixture of grains of feldspar, quartz, and mica.

Many common rock names are loosely used, and this often leads to trouble. In letting contracts for quarrying, tunneling, etc., the contractor may often base his estimates on the nature of the rock to be removed, and neglect on the part of either party to properly identify or designate the kind of material to be taken out has not infrequently led to serious misunderstanding and disagreement, inconvenient as well as expensive to one party or the other.

The common minerals which enter into the composition of rocks have been treated at length in Chapter I.

In the study of rocks the following essential features should be considered before describing the individual types under each of the three main divisions named below: (1) Mode of occurrence or geological relations; (2) composition or character of the component minerals; (3) texture or manner of aggregation of the component minerals; and (4) structure or mode of arrangement. These subjects are treated in the following pages of this chapter, and in every case the practical bearing is pointed out so far as is possible.

Varieties of rocks. — Many principles have been made the bases of various schemes for grouping or classifying rocks, among the more important of which may be mentioned: (*a*) texture and structure; (*b*) mineralogical composition; (*c*) chemical composition; (*d*) geological age; (*e*) origin or genesis; or a combination of several of these. A discussion of these is not only unnecessary but beyond the scope of this book.

Based on the principle of genesis or mode of origin rocks may be grouped into three large classes, now recognized quite generally by all geologists. These are:

(I) *Igneous rocks,* those which have solidified from molten material.

(II) *Sedimentary rocks* (also called *stratified* rocks), those which have been laid down chiefly under water (*aqueous*) by mechanical, chemical, or organic agents. Under this division is included also a smaller group of wind-formed rocks (*æolian*).

(III) *Metamorphic rocks,* those which have been formed from original igneous or sedimentary rocks by alteration, through the action of subsequent processes (the work chiefly of pressure, heat, and water), which have resulted in wholly or partly obscuring their original characters.

These three divisions will be adopted in the following pages, each division being separately treated in the order named.

IGNEOUS ROCKS

Occurrence and Origin

When fresh and unaltered the igneous rocks frequently possess certain characters by which they may be distinguished from the sedimentary and metamorphic ones.[1]

[1] The igneous rocks forming the walls of some ore deposits are sometimes so altered by hot ascending solutions, that it is difficult to identify them, except by careful microscopic study. (See Chapter on Ore-Deposits.)

The evidence gained by careful study in the field as to the mode of occurrence or geologic relations of the rocks to surrounding ones whether formed as dikes, lava sheets, etc., will frequently determine the igneous origin of a rock. Again, mineral composition serves as an important distinguishing characteristic. If composed wholly or partly of glass, the rock is certainly of igneous origin; or, if made up entirely of mineral aggregates, the presence of certain minerals is usually regarded as strong evidence of igneous origin. Finally, structure and texture oftentimes furnish an important means of identification. An igneous rock usually appears homogeneous and massive, without evidence of stratification[1] and foliation or banding, structures that are common to sedimentary and metamorphic rocks, although occasionally observed in some igneous masses (for example volcanic tuffs). Amygdaloidal texture (p. 69) is characteristic of many surface lava flows. At times the igneous rock may, by its temperature or in other ways, have altered the surrounding rock near the contact in a characteristic manner. Fossils are not found in igneous rocks, except rarely in tuffs.

Mode of Occurrence

As previously stated, igneous rocks have been formed by the consolidation of molten material, the source of which was within the earth at some unknown depth beneath the surface. At times and in various localities, this molten material under proper conditions is forced upward for one cause or another towards the surface of the earth, cutting through or intruding any other kind of rock. It may be arrested at some depth below the surface where it is cooled and solidified under the influence of the surrounding rocks, or it may reach the surface and be poured out upon it, solidifying to form hard rock.

This conception leads to a two-fold division of igneous rocks. (1) Those that have solidified at considerable depths beneath the surface, designated *intrusive* or *plutonic;* and (2) those that have solidified at or on the surface, designated *extrusive* or *volcanic.* Each of these may be further subdivided.

Intrusive or Plutonic Rocks

Forms of intrusive rocks. — The principal modes of occurrence of intrusive igneous rocks recognized by geologists are as follows: *Dikes, sheets, laccoliths, necks, stocks,* and *batholiths.*

[1] Occasionally regular horizontal jointing is mistaken for stratification by persons having but slight geological knowledge.

PLATE I, FIG. 1. — Parallel dikes of diabase cutting pegmatite dike, near Pourpour, Quebec. (H. de Schmid, photo.)

FIG. 2. — Irregular granite dikes cutting gneiss, Moose Mountain, Ont. (H. Ries, photo.)

Dikes. — A dike results from the filling of a fissure in other rocks (Plate I) by molten material from below, and there solidified. It is the simplest form of intrusion, and has great length as compared with thickness; hence, it is an elongated and relatively narrow body, which may range from a fraction of an inch in width and a few yards in length to a hundred feet and more across and miles in length. In inclination dikes may vary from vertical to horizontal, the most frequent attitude being that of vertical or nearly so.

Frequently they may be observed extending outward from larger masses of intruded rock (Fig. 52), but in many cases such a relationship is not visible. They may continue along remarkably straight lines or follow irregular or sinuous courses (Plate I, Fig. 2). A large dike may divide into two or more smaller ones which continue usually in the same general direction, and apophyses or stringers are common. The igneous rock of the dike may be acid or basic in character, and

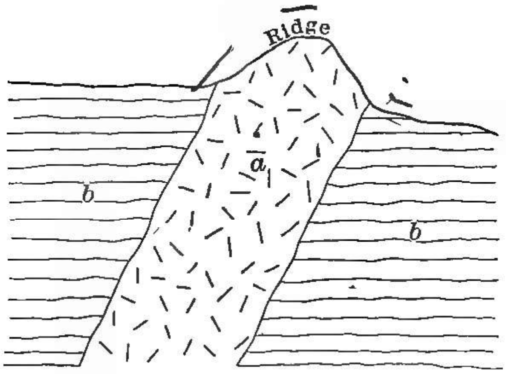

Fig. 47. — Section through dike more resistant to weathering than the inclosing rock, marking the position of a ridge. (*a*) dike; (*b*) inclosing rock.

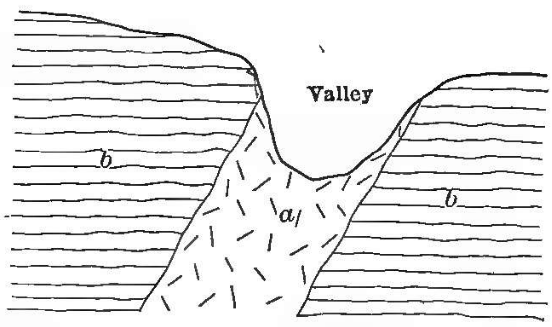

Fig. 48. — Section through dike less resistant to weathering than the inclosing rock, marking the position of a valley. (*a*) dike; (*b*) wallrock.

dikes of each are common over many parts of the eastern or Atlantic province of crystalline rocks (see plate showing granite areas in Chapter XI). The large dikes almost invariably show finer-grained texture along the margins than in the centers, whereas the narrow dikes are apt to be fine-grained throughout. Also some of the large dikes show alteration of the inclosing rocks along the contacts.

Subsequent erosion and weathering of a dike may or may not result in topographic expression (Figs. 47 to 49). Usually if the dike rock is more resistant to weathering and erosion than the inclosing rocks, the position of the dike will be marked by a ridge (Fig. 47). Sometimes the opposite effect is shown and a valley-like depression results (Fig. 48). Again, it frequently happens that no topographic expression is shown (Fig. 49), and as in the crystalline province of the eastern United States, the only surface indication remaining to mark the position of the dike is a line of large and small boulders of the original dike scattered loose over the surface and partly buried in the resulting residual rock decay (clay) (Plate XXXI).

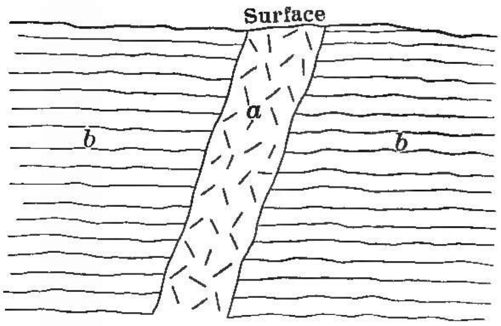

FIG. 49. — Section through dike and inclosing rock, showing no topographic expression from weathering. (*a*) dike; (*b*) inclosing rock.

Dikes are so abundant that the engineer frequently encounters them in the field. They are often not of any value as road or building material, because of their narrow width, and their occurrence in quarries (Plate VI, Fig. 1) is objectionable because they spoil the stone, and sometimes crack it up badly. Abundant dikes therefore may mean much waste, unless the defective stone can be broken up for road material.

In some localities the dike rock may be weathered (but not eroded) to such an extent that it permits access of surface water. If then these decayed dikes are encountered in underground operations, the water seeping downward along them may give trouble.[1]

Ore bodies sometimes but not always are associated with dikes, while at other times a dike of later age may cut across the ore deposit, a condition which has sometimes been misinterpreted, and led to the belief that the ore had given out.

Another case of error has been caused by the occurrence of somewhat broad parallel dikes, whose adjoining boundaries were hidden by surface material, leading the engineer to suspect that the two were one large dike.

Intrusive sheets. — Intrusive sheets, known also as *sills*, are the solidified bodies of molten material intruded between the stratification or foliation planes of sedimentary and metamorphic rocks, and hence they assume a somewhat bedded aspect (Fig. 50). They are characterized by relatively great lateral extent as compared with their thickness. Probably the basic and intermediate igneous rocks, such as andesites and basalts, assume the form of intrusive sheets more frequently than the acid rocks.

Sheets may range from a foot to several hundred feet or more in

[1] A band of clayey rock encountered underground does not always represent decayed dike rock, but is sometimes rock which has been first crushed by movement along a fracture (faulting), and subsequently weathered by percolating water.

thickness, and may cover an area many miles in extent. "The Palisades of the Hudson are formed by a sheet of unusual thickness; its out-

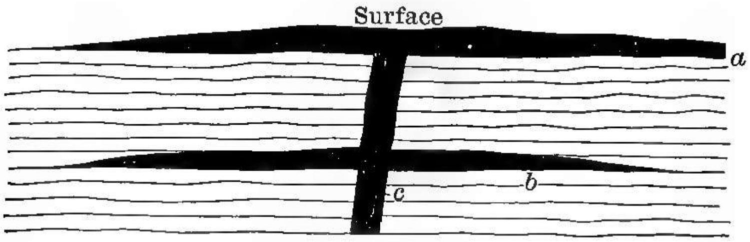

FIG. 50.—Section through (a), extrusive and (b) intrusive sheets, and (c) conduit.

crop is 70 miles long from north to south, and its thickness varies from 300 to 850 feet" (Scott). Sheets sometimes break across the strata and are continued at a new horizon (Fig. 51). Frequently thick sheets

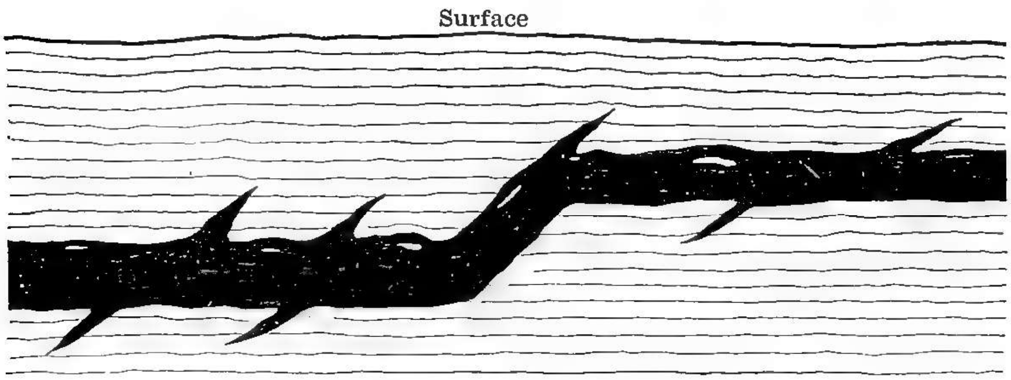

FIG. 51. — Section of intrusive sheet, breaking across the strata and continuing in the same general direction at a higher horizon; sheet shows apophyses and inclusions of country rock.

or sills divide into several subordinate ones, each following more or less closely a plane of bedding.

Intrusive sheets may sometimes be mistaken for surface lava flows that have subsequently been buried. They may often be distinguished from contemporaneous sheets or flows by (*a*) alteration by heat of the beds immediately above and below; (*b*) breaking across the beds at any point and continued along another horizon; (*c*) giving off of tongues or apophyses into the overlying as well as underlying beds; (*d*) the general absence from the upper surface of scoriaceous or tuffaceous material and of vesicular and amygdaloidal textures (which see); (*e*) incorporation of rock fragments in the sheet torn from the overlying bed, etc.

Sheets or sills do not always show the same mineral composition from top to bottom (see magmatic differentiation, p. 70). Where such variation exists the rock may be dark-colored or basic at the bottom and lighter-colored and siliceous at the top, affording two different types of building stone. Such a difference exists in the sill of Sudbury, Ontario, where the nickel-copper ores are found only in the basic or lower portion of the sill. Sheets or sills are not of much importance as a source of building stone.

Laccoliths. — A laccolith is a lenticular or dome-shaped mass of igneous rock intruded between strata. It may be considered as a special case of an intrusive sheet in which the supply of molten material from below exceeds the rate of lateral spreading, and is accompanied by arching of the overlying beds at the surface. A section through the igneous mass usually shows a flat base and a convex upper surface (Fig. 52), resembling a half lens. Figs. 52 and 53 show variations in

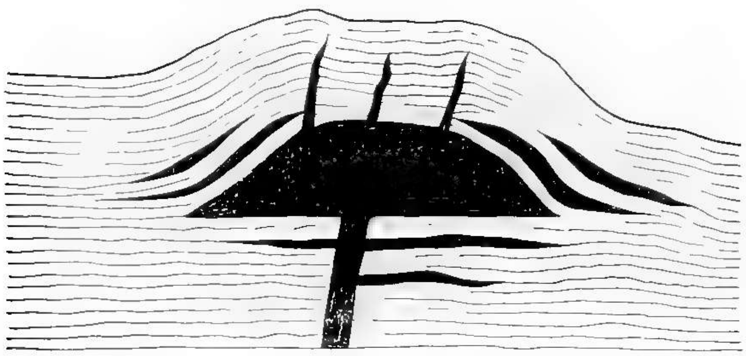

FIG. 52. — Section through laccolith showing associated sheets and dikes. Compare outline of laccolith with that of Fig. 53.

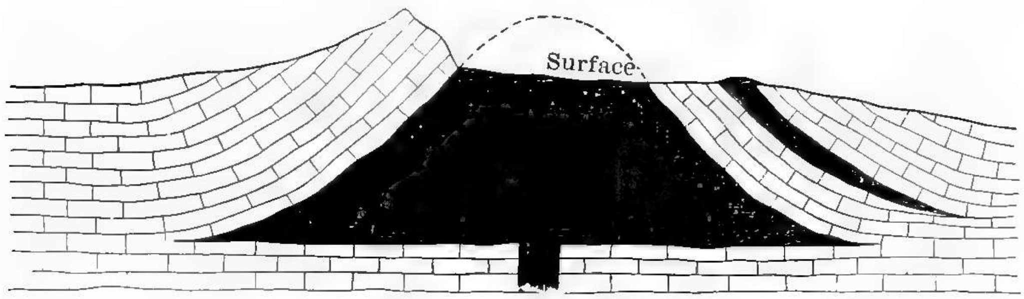

FIG. 53. — Section through partly eroded laccolith showing different outline from Fig. 52.

the general structure of laccoliths due probably, as has been suggested by some, to progressive increase of viscosity of the magma during its intrusion. In plan the mass approximates a circle, but may be somewhat elongated and oval-shaped, and in size (thickness and lateral extent) is subject to great variation. In some cases the laccolith is accompanied by intrusive sheets and dikes (Fig. 52), and like the latter they may and do frequently alter by metamorphism the overlying and underlying beds. The pressure of the intruded magma forming the laccolith usually causes a lifting of the overlying strata and produces a dome-like elevation at the surface (Fig. 52). Laccoliths may occur singly, though they often occur in groups, a dozen or more being clustered together in some instances.

The Henry Mountains of Utah, first described by G. K. Gilbert, form a typical representative of the laccolithic method of intrusion. Here, many stages of erosion are represented and may be observed. Many other examples of laccoliths are known in the western United States and in Europe.

Laccoliths, like sills, may sometimes show a zonal structure, and hence the center and margins might supply different kinds of rock.

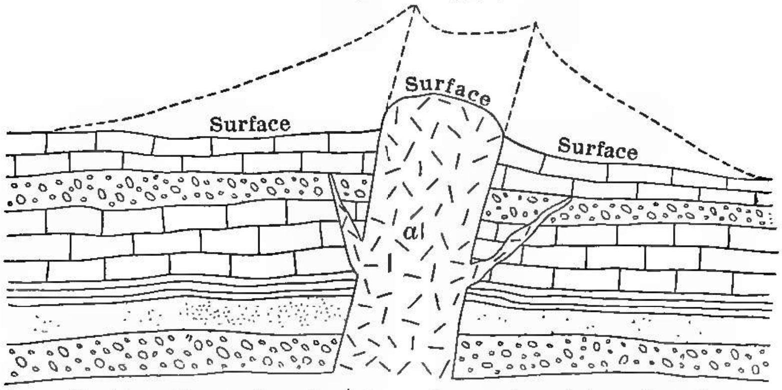

FIG. 54. — Section through volcanic neck or plug (*a*), volcanic cone shown by dotted lines, removed by erosion.

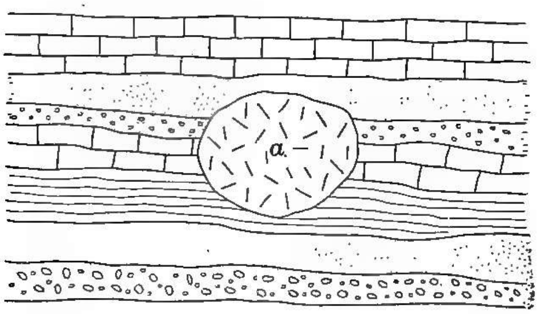

FIG. 55. — Plan of volcanic neck or plug (*a*).

Necks. — These are roughly cylindrical masses of igneous rock having probably great but unknown depth, which fill the vents or conduits of volcanoes. Erosion may remove practically all trace of the surrounding beds of more porous and softer volcanic ejectments, leaving the plug of resistant, consolidated igneous rock as a more or less conspicuous topographic form (Fig. 54). Volcanic necks may range up to a mile or more across, and are usually more or less circular in plan (Fig. 55). Good examples of necks are noted in places over the western half of the United States, especially those of western New Mexico.

Stocks. — Stocks, known also as *bosses*, are irregular, rounded masses of igneous rock intruded and solidified at some depth beneath

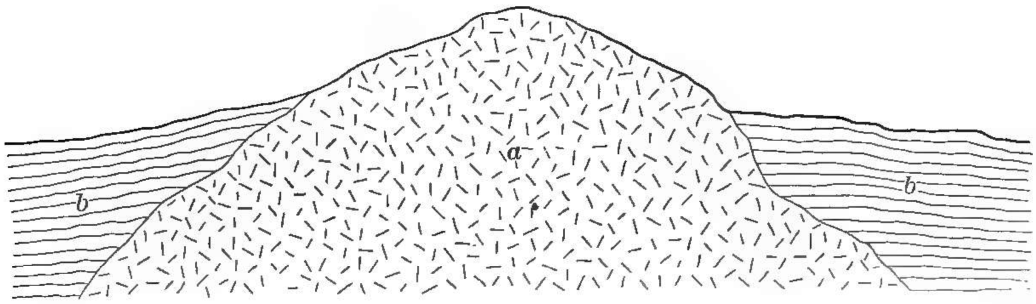

FIG. 56. — Section through stock or boss. (*a*) granite boss; (*b*) inclosing rock.

the surface, and now exposed from stripping by erosion of the thickness of overlying rocks (Fig. 56 and Plate XXXIV, Fig. 2).

Stocks may range in size from a few hundred feet to several miles; and in plan they may vary from more or less circular to elliptical in outline (Fig. 57). They may cut across the inclosing (country) rock

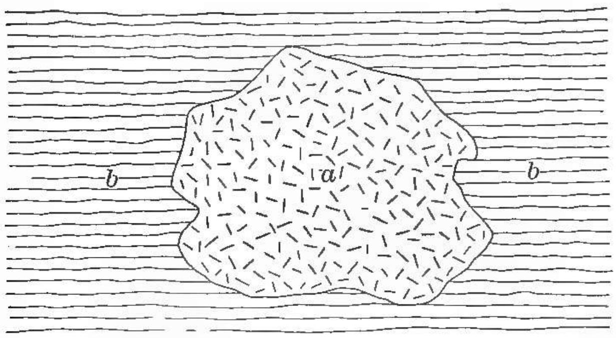

FIG. 57. — Plan of stock or boss. (*a*) granite; (*b*) inclosing rock.

with frequently steeply-inclined contacts, along which characteristic metamorphism is often observed.

Because the rock, especially granite, composing stocks or bosses is frequently of more resistant character than the surrounding or country rock, they become dome-like masses of steep or gentle slopes, and oftentimes on account of size are conspicuous topographic forms (Plate XXXIV, Figure 2). Many of them show an elevation of several hundred feet, and in extreme cases 700 or 800 feet and more above the surface of the surrounding rocks, such as Stone Mountain, Georgia, and the splendid granite domes of the Yosemite in California. On the other hand in regions of old land surfaces which have been continuously exposed to weathering and erosion for very long periods of time, the surface of the boss shows no topographic expression, but is more or less flat and coincident with that of the inclosing rocks.

Batholiths. — These are huge masses of plutonic rock hundreds of miles in extent which are now exposed at the surface by erosion (Fig. 58). They are similar to stocks, but differ from them mainly in their much larger size, the small batholith and the large stock grading into each other. If they could be followed down, probably many stocks would prove to be protrusions from batholiths (Fig. 58). Batholiths are shown in the oldest regions of the earth, such as eastern Canada, etc., or forming the core of many mountain ranges, like the Sierra Nevada and Rocky Mountains. They usually consist of some granitoid rock, such as granite, syenite, diorite, etc., but probably granite is the commonest rock forming them. The country rock surrounding them is also variable.

Both batholiths and stocks are important sources of granitic rock for use in structural work. The massive character of the rock, and the arrangement and spacing of the joints make the material well adapted for the extraction of dimension blocks.

In the West important ore bodies are sometimes found along the borders of such batholiths.

Extrusive or Volcanic Rocks

These may be (*a*) molten material poured out onto the surface from a volcanic vent or along a fissure and solidified, or (*b*) fragmental material (*pyroclastic*) of all sizes erupted from volcanic vents. The first forms surface *lava flows* and *sheets*, the second *ash-beds* (Plate VI, Fig. 2), and coarser fragmental material, which on consolidation yield beds of *tuffs* and

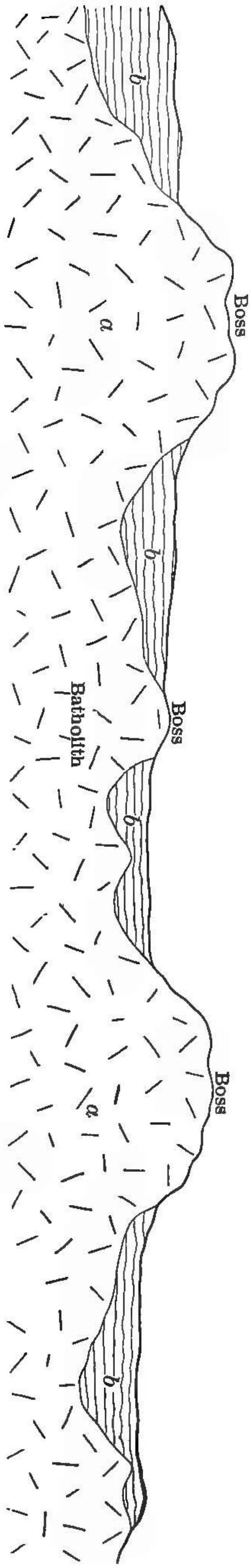

Fig. 58. — Section through a batholith. (*a*) granite; (*b*) schist.

volcanic *breccias*. The crystalline (lava flows) and fragmental materials frequently occur interstratified as shown in Fig. 59. The fragmental materials show all varieties of texture and structure, some being very fine-grained while others are very coarse, but bedding is usually pronounced.

Lava flows and sheets. — These are formed on the surface from quiet outwellings of highly molten material through (*a*) a localized opening or volcanic vent and hence connected with volcanic eruptions, or (*b*) from fissures not connected with volcanic eruptions. The lava flow may be either *subaerial* (on land) or *submarine*, according to whether the eruption takes place on land or on the sea bottom. The flows vary much in thickness, some being only a few feet while others are measured in yards.

Subaerial flows from volcanic vents may build cones having very low angles of slope and of great lateral extent, according to the fluidity of the lava erupted, such as the volcanic cones of Hawaii and Iceland. Thus the more basic lavas are the more fluid. These may alternate

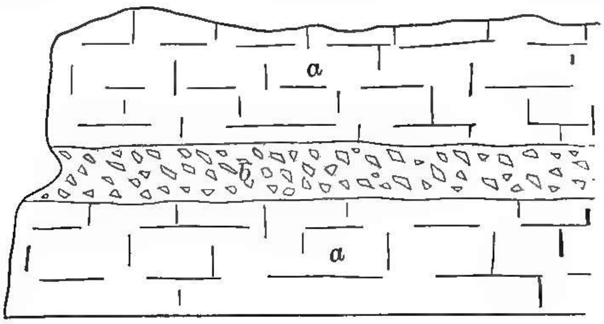

Fig. 59. — Section through a series of interbedded lava flows, and fragmental materials. (*a*) lava flows; (*b*) fragmental materials.

with extrusions of fragmental material (Fig. 59), when a cone of composite character and steeper slopes is formed (Plate II, Fig. 1).

In many places over the earth's surface lava flows have resulted from the quiet outpouring onto the surface through fissures, spreading in some cases hundreds of miles in extent and several thousand feet in thickness. Such *fissure-eruptions* have occurred on a gigantic scale in the Columbia River region of the northwestern United States, in eastern India, in the north of the British Isles, and in historic times in Iceland.

In some cases surface lava sheets have later become buried by deposition of other rocks on them through depression below sea-level. In such cases the buried sheet resembles one of intrusion, but can usually be distinguished from the latter by absence of metamorphism of the overlying beds, and the structures characteristic of the surface of lavas, such as scoriaceous, amygdaloidal, vesicular, etc.

PLATE II, Fig. 1. — Volcanic cone of Colima, Mexico. Built up of ash and lava flows. Parasitic cone of 1865 on left. Ridge in foreground part of base of original cone destroyed by an explosive eruption. (H. Ries, photo.)

Fig. 2. — Table Mountain, Golden, Colo. Capped by several flows of resistant basalt. Under these upturned beds of sedimentary rocks. (H. Ries, photo.)

The fragmental (pyroclastic) materials are those which have been thrown out with great force and in enormous volume, during violent volcanic eruptions. They have settled down over the surrounding country, either on land (Plate VI, Fig. 2) or in water, and hence often show a stratified structure.

In the western states and Mexico, where these volcanic rocks are abundant the engineer has to deal with them.

Lava flows, though often thick, are sometimes shallow, and overlie stream gravel or other deposits (Plate XLIII, Fig. 1). When testing a rock foundation for dams, reservoirs or other structures, which are to be placed on lava flows, care should be taken to see that the lava cap is sufficiently thick to give a solid and impermeable base.[1]

Lava flows are not as a rule adapted to the production of large blocks. Many show a columnar jointing (Plate III, Fig. 2). The stone at the surface of the flow may be broken up (Plate III, Fig. 1), or if massive is often full of gas cavities, which may be absent deeper down (Plate III, Fig. 2).

The more porous and softer volcanic rocks, like tuffs and agglomerates, can often be cut into larger blocks than the consolidated lavas. They are however usually very porous, and should not if possible be used in moist situations. Curiously enough however many of these very porous volcanic rocks are not injured by frost, probably because they do not absorb enough water to completely fill their pores. (See absorption under Building Stones.)

The high porosity of tuffs and breccias may also cause trouble in dam and reservoir construction, because they permit seepage under the walls, so that the bed rock may have to be filled with grout, or sealed up in other ways. In the case of one dam foundation on the Clackamas River in Oregon, grout forced down a 50-foot pipe under a 200 pounds pressure, crossed a six-foot interval in the volcanic breccia, rushed up another pipe to the surface and spurted 30 feet into the air. For similar reasons a tunnel driven through them should be lined.

The use of volcanic ash for hydraulic cement is referred to in Chapter XII.

Composition of Igneous Rocks

Under this heading is discussed (*a*) *chemical* and (*b*) *mineralogical* composition of igneous rocks. As previously stated, most igneous rocks are made up of mineral aggregates. For such rocks mineral composition is dependent in large measure on chemical composition of the

[1] For example see case of Zuni Dam, *Eng. News*, LXIV, p. 203, 1909.

rock magmas.[1] When solidified under different physical conditions, rock magmas having similar chemical composition may yield different minerals; and differences in chemical composition usually result in variations in mineral composition. Chemical composition plays a fundamental role in the classification of igneous rocks, as discussed later.

Chemical composition. — It is obvious that rock magmas as such cannot be subjected to chemical analysis, but their solidified products (rocks) can; and from the very large number of analyses made of igneous rocks from all parts of the world, they are shown to be, without exception, silicate magmas. The many hundreds of analyses that have been made of igneous rocks invariably show that they contain the following principal oxides: *Silica* (SiO_2); *alumina* (Al_2O_3); iron oxides, *ferric* (Fe_2O_3) and *ferrous* (FeO); *magnesia* (MgO); *lime* (CaO); *soda* (Na_2O); and *potash* (K_2O). Other lesser oxides, including water, are present, but no account is taken of them here, since they usually occur in such small amounts that they do not exert any important influence on the rock.

Igneous rocks show varying chemical composition, which is used by the geologist to study their relationships, but to the engineer chemical analysis is not of much practical value. Igneous rocks form a series ranging from acid ones (high in silica), with dominant alkali feldspar and quartz, to basic ones (low in silica) with ferromagnesian silicate minerals predominating.

Since the acid magmas contain silica in excess of the bases, these will develop free quartz in the rocks crystallized from them. The total percentage of silica in them may reach 80 per cent. On the other hand, many magmas are low in silica, as shown in the analyses of the rocks formed from them. In the basic rocks the percentage of silica may be as low as 40 per cent, and in some ultrabasic ones it may be even lower, not exceeding 30 per cent. The amount of silica present exercises an important influence on the crystallization of the magma, as discussed later.

The eight principal oxides enumerated above as composing igneous rocks do not exist as free oxides except in a few cases and with but few exceptions only in small amounts. Of these the iron oxides are the most frequently occurring ones, although alumina as the mineral corundum is sometimes present. With these exceptions, the oxides of aluminum, iron, magnesium, calcium, sodium, and potassium are combined in the form of silicate minerals, which, with rare exceptions, compose the igneous rocks.

Alumina may range from nothing in some of the nonfeldspathic rocks, such as the peridotites, to 20 per cent and more in some syenites. It is present chiefly in

[1] Magma is now generally employed for the molten masses of igneous rock before they have crystallized. An original parent magma may break up into several derived ones. J. F. Kemp, Handbook of Rocks, 1906, p. 202.

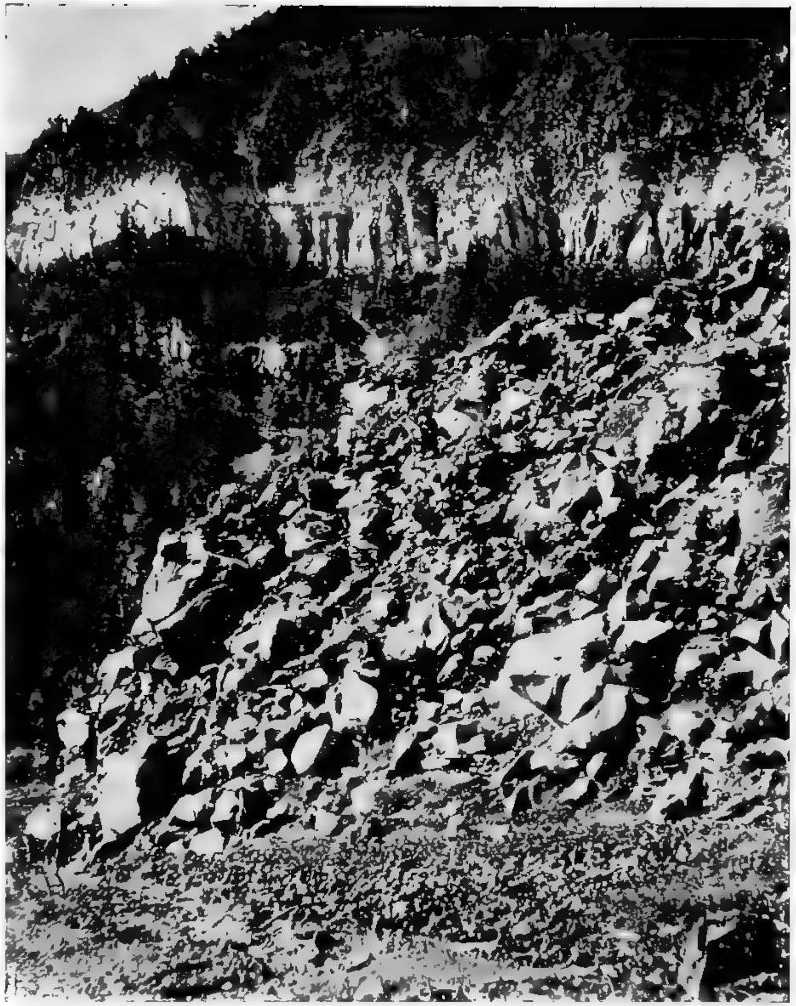

PLATE III, Fig. 1. — End of an *a–a* flow of lava, Colima, Mex. (H. Ries, photo.)

Fig. 2. — Basalt lava, near Mexico City, Mex.; shows rudely columnar jointing, and gas cavities in upper portion. Quarried for paving blocks. (H. Ries, photo.)

rocks in combination with silica and the alkalies, and in some cases lime, as feldspars and feldspathoids. It also enters into the composition of some of the so-called ferromagnesian minerals, such as mica, hornblende, augite, etc. As noted above, alumina is sometimes present in rocks as the mineral corundum.

The oxides of iron and magnesium combine with silica to form the so-called ferromagnesian minerals, which comprise the pyroxene, hornblende, biotite, and olivine groups as the principal rock-forming ones (see Chapter I). Lime enters into combination with the same bases and silica in the monoclinic pyroxenes and amphiboles, and is an important constituent in the more calcic (basic) plagioclase feldspars. It is essentially absent from the orthorhombic pyroxenes and biotite.

The ferromagnesian minerals are usually present in only subordinate amounts in the acid rocks, but increase in quantity and are the predominant minerals in the basic rocks.

The alkalies, potash and soda, in combination with alumina, silica, and in some cases lime, are of fundamental importance in the feldspars (orthoclase and plagioclase groups), and the feldspathoids. They are, especially soda, important constituents in the alkali-rich pyroxenes and amphiboles; and potash enters into the composition of biotite.

Phosphoric anhydride (P_2O_5) and titania (TiO_2) among the lesser oxides are quite generally present in igneous rocks; the former in combination with lime as the mineral apatite is of most importance in the basic rocks; while the latter occurs as free oxides in the minerals ilmenite and sometimes rutile, as the lime titano-silicate sphene, the lime titanate perovskite, and in variable but small quantities in the ferromagnesian silicates.

Boron, fluorine, and chlorine frequently occur in minute quantities in igneous rocks; as do also sulphur and carbon, the former as sulphides, especially as the mineral pyrite, and the latter in elementary form as graphite.

The annexed table will serve in some measure to give a general idea of the composition of the principal types of plutonic igneous rocks. Analyses of the corresponding volcanic rocks are omitted from the table, since they have similar composition to their equivalent plutonic types.

TABLE OF ANALYSES OF PLUTONIC IGNEOUS ROCKS

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
SiO_2	72.27	65.43	60.39	70.36	62.71	46.85	45.05	33.84
Al_2O_3	14.30	16.11	22.57	15.47	17.06	19.72	6.50	5.88
Fe_2O_3	1.16	1.15	0.42	0.98	3.79	3.22	3.83	7.04
FeO	0.97	2.85	2.26	1.17	2.74	7.99	7.69	5.16
MgO	0.70	0.40	0.13	0.87	1.78	7.75	12.07	22.96
CaO	1.56	1.49	0.32	3.18	5.51	13.10	18.82	9.46
Na_2O	3.46	5.00	8.44	4.91	3.54	0.09	0.94	0.33
K_2O	5.00	5.49	4.77	1.71	2.96	1.56	0.78	2.04
Rest	0.83	2.26	0.65	1.43	0.14	0.56	5.20	13.83
	100.25	100.18	99.95	100.08	100.33	100.84	100.88	100.54

I. Biotite granite, near Richmond, Virginia; II. Syenite, Mount Ascutney, Vermont; III. Nepheline syenite (Litchfieldite), Litchfield County, Maine; IV. Quartz diorite, near Enterprise, Butte County, California; V. Diorite, Bush Creek, Elk Mountains, Colorado; VI. Gabbro, Baltimore, Maryland; Average of 23 samples: VII. Pyroxenite, Brandberget, Norway; VIII. Peridotite, Crittenden County, Kentucky.

Study of this table of analyses of the principal types of plutonic igneous rocks discloses wide variations in the eight chief component oxides. Silica, alumina, and the alkalies (soda and potash) are the principal components in the most acid rock granite, which indicates that feldspar and quartz are the dominant minerals. As the basic and ultrabasic types are approached, these oxides decrease in quantity and the oxides of iron, magnesium, and calcium increase, which, when expressed mineralogically, emphasizes the increase of ferromagnesian minerals with decrease of quartz and feldspar; the former being quite generally absent and the latter (feldspar) failing entirely in the ultrabasic rocks.

F. W. Clarke has calculated the average composition of igneous rocks, based on the most reliable data available, to be as follows:

TABLE SHOWING AVERAGE COMPOSITION OF IGNEOUS ROCKS
(Reduced to 100 per cent)

SiO_2	59.93
Al_2O_3	14.97
Fe_2O_3	2.58
FeO	3.42
MgO	3.85
CaO	4.78
Na_2O	3.40
K_2O	2.99
H_2O	1.94
Rest	2.14
	100.00

Under "rest" in the table above is included TiO_2, ZrO_2, CO_2, P_2O_5, S, Cl, F, BaO, SrO, MnO, NiO, Cr_2O_3, V_2O_3, and Li_2O.

Mineral composition. — Most igneous rocks are aggregates of minerals; a few are composed wholly of glass, and still others are made up of a mixture of minerals and glass. Given magmas of similar chemical composition and vary the physical conditions of cooling on solidifying, and development of different minerals will result.

The mineral composition affects the hardness, durability, beauty, and ability of the rock to take a polish.

From the discussion under "chemical composition" it has been shown that the principal oxides found on analysis are combined with each other to form silicate minerals, the chief components of igneous rocks. The important groups of these include feldspars, quartz, and the ferromagnesian minerals. For convenience of classification the more important minerals of igneous rocks may be tabulated under two groups as follows:

Siliceous-aluminous Group (Salic).	Ferromagnesian Group (Femic).
Alkalic feldspar	Pyroxenes
Plagioclase feldspar	Amphiboles
Quartz	Biotite
Nephelite	Olivine
Sodalite	Iron ores
Corundum	

Considered mineralogically, the acid rocks are characterized by the presence of dominant alkali feldspar and more or less quartz, with subordinate ferromagnesian minerals. They are rich in silica, alumina, and alkalies, but contain only small amounts of iron, lime, and magnesia, hence these rocks are usually light in color, have a low density or specific gravity (average about 2.6), and comparatively high fusion point.

Intermediate rocks contain little or no quartz, but consist chiefly of alkalic and soda-lime feldspars, with in some cases the feldspathoids (nephelite, sodalite, etc.), with or without ferromagnesian minerals.

In the basic igneous rocks ferromagnesian minerals predominate; the dominant feldspar is a member of the lime-soda series, quartz is absent, and olivine is frequently present. They contain less silica and alkalies than the acid rocks, but are higher in iron, lime, and magnesia. The rocks are, therefore, much more fusible, are dark in color, and have a relatively high density or specific gravity, being about 3.0 to 3.2, reaching in the ultra-basic rocks as much as 3.6.

In the ultrabasic rocks, both feldspar and quartz are essentially absent, and one or more of the ferromagnesian minerals is the dominant component, either hornblende, a pyroxene, olivine, or a mixture of these.

According to F. W. Clarke,[1] "a statistical examination of about 700 igneous rocks, which have been described petrographically, leads to the following rough estimate of their mean mineralogical composition:"

Quartz	12.0
Feldspars	59.5
Hornblende and pyroxene	16.8
Mica	3.8
Accessory minerals	7.9
	100.0

Grouping of minerals. — A convenient and useful division of the rock-forming minerals which enter into the composition of igneous rocks is into (*a*) *essential* and (*b*) *accessory*. Essential minerals influence greatly the character of a rock and their presence is therefore necessary for the naming of it. For example, quartz with certain other minerals is essential to the naming of a rock granite, but if quartz be practically absent or present in only very small amount the rock composed of the same mineral aggregates would be designated a quartzless granite or syenite.

On the other hand, accessory minerals occur only sparingly or in small quantity and their presence or absence does not materially affect the nature of the rock. Thus, quartz and feldspar are essential minerals in granite, while zircon and apatite are accessory.

Another important distinction that is frequently made between minerals of igneous rocks is whether they are *original* or *secondary*. Original minerals, known also as pyrogenetic or primary, have formed

[1] The Data of Geochemistry, 1911, Bull. 491, U. S. Geol. Survey, p. 30.

from the solidification of the magma, while *secondary* minerals have formed subsequent to the crystallization of the magma, and from the original ones by alteration (weathering, contact or dynamic metamorphism, etc.). Thus kaolinite, sericite, talc, calcite, and epidote are secondary minerals in igneous rocks.

Essential minerals are original, but not all original minerals are essential. For example, quartz and feldspar in granite are both essential and original minerals, while zircon and apatite in the same rock are original, but they are not essential minerals. An essential mineral may sometimes be replaced by a secondary one, such as hornblende (uralite) which replaces pyroxene in gabbros that have been subjected to metamorphism.

Order of crystallization. — The order in which minerals crystallize from a magma is indicated by the mutual relations of the components as viewed in thin sections under the microscope, or, as in the case of coarse-grained rocks, from polished surfaces. Thus far experience shows that minerals crystallizing from magmas do so not simultaneously but successively, with in some cases overlapping of their periods of crystallization, as shown in quartz and feldspar, from the study of thin sections of granite.

Rosenbusch states that in general the order of crystallization of minerals from magmas is in four groups as follows:

I. Iron ores and accessory constituents (magnetite, hematite, ilmenite, apatite, zircon, spinel, sphene, etc.).

II. Ferromagnesian silicates (olivine, pyroxene, amphibole, mica, etc.).

III. Feldspathic constituents (feldspars and feldspathoids, including leucit nephelite, sodalite, etc.).

IV. Free silica (quartz).

This order of crystallization applies especially to nonporphyritic rocks. "More explicitly," as Harker[1] states, "what is regarded as the normal sequence is laid down in the following rules:"

I. "The separation of crystals in a silicate-magma follows an *order of decreasing basicity*, so that at every stage the residual magma is more acid than the aggregate of the compound already crystallized out."

II. "The relative amounts of the several constituents present in the magma affect the order of crystallization in such a manner that, in general, those present in smaller amount crystallize out first."

III. "Having regard to the several bases represented in the various constituents crystallization begins with the separation of iron oxides and spinellids, proceeds with the formation of magnesium and iron silicates, then silicates of calcium, then those of the alkali metals, and ends with the crystallization of the remaining free silica."

Mineralizers. — Study of extrusive lavas at the time of expulsion shows the presence of considerable quantities of volatile substances, chief among which is water vapor. Besides water vapor there are

[1] The Natural History of Igneous Rocks, 1909, pp. 180–181.

carbon dioxide, fluorine, chlorine, boric acid, sulphur, etc. These dissolved vapors, known as *mineralizers*, for the reason that they exercise an important influence on mineral composition and to some extent texture, are regarded as being more generally present in acid than in basic magmas, although known to occur in both. These substances play an important role in the crystallization of igneous rocks, and their action in the production of minerals from solidifying magmas may be either chemical or physical.

For the formation of certain minerals, such as hornblende, biotite, tourmaline, etc., which contain small quantities of water as hydroxyl (OH), fluorine, and boric acid, the presence of mineralizers in the magma is essential, and their function is a chemical one. On the other hand, many minerals cannot be produced by dry fusion, but require for their production the presence of certain mineralizers, especially water vapor, which acts physically in lowering the melting point of the fusion and increasing its fluidity, as in the formation of orthoclase, albite, and quartz.

Texture of Igneous Rocks

By *texture* of an igneous rock is meant size, shape, and manner of aggregation of its component minerals. It serves an important means of determining the physical condition under which the rock was formed, whether at or near the surface, or at some depth below, and hence is recognized as one of the important factors in the classification of igneous rocks.

Some rocks are sufficiently coarse-grained in texture for the principal minerals to be readily distinguished by the unaided eye; in others the minerals are so small in size as to defy identification by the naked eye or even with the aid of a pocket lens; and in still others no minerals have crystallized, but, instead, the magma has solidified as a glass. These express the physical (rate of cooling) and not the chemical conditions under which magmas have solidified, and in turn serve in a general way to express the position in the earth's crust in which this solidification took place. The rate of cooling, therefore, is one of the most prominent factors in determining rock texture. Other important factors that influence the development of rock texture are chemical composition, temperature, pressure, and the presence of mineralizers.

Kinds of texture. — Since texture expresses so closely the conditions under which rock magmas solidify, it is recognized as an important property of rocks, and is made one of the principal factors in their classification (see page 70). In the megascopic description of igneous rocks, including their pyroclastic (volcanic) equivalents, five principal textures are recognized. These are *glassy*, *dense or felsitic* (*aphanitic*), *porphyritic*, *granitoid*, and *fragmental*.

Glassy texture. — Under conditions of quick chilling, magmas, especially the more siliceous ones, freeze or solidify into a glass, without distinct crystallization and the formation of visible minerals. Such rocks do not show definite minerals and are composed of glass, examples of this being obsidian, pitchstone, etc. Some glasses, such as *pumice,* are highly vesicular due to the escape of water vapor at high temperature through relief of pressure.

Dense or felsitic (aphanitic) texture. — This texture is characteristic of crystalline rocks, but the individual minerals are too small in size to be distinguished by the eye. The general appearance of the rock is homogeneous and stony but not glassy. Examples, many felsites and basalts.

Porphyritic texture. — Porphyritic texture is characteristic of those rocks composed of mineral grains or crystals of larger size set in a groundmass (Plate IV, Fig. 2) that is more finely crystalline or even glassy, or both. The larger crystals or grains are termed *phenocrysts* and may show distinct crystal outline (*idiomorphic*), or may have irregular and corroded surfaces (*allotriomorphic*). They may be very abundant in some rocks, exceeding occasionally the groundmass in amount, or they may be very scantily developed. Great variation in size is also shown, from an inch and more in diameter down to those so small that they are scarcely discernible. They may consist of the light-colored minerals (quartz and feldspar) or of the dark-colored ferromagnesian ones (hornblende, pyroxene, olivine, etc.), or of a mixture of light- and dark-colored minerals.

Porphyritic texture is frequently developed in lavas, dikes, sheets, and laccoliths, and is less often observed in the deeper-seated rocks, but by no means uncommon in some, as in granites.

In porphyritic rocks the groundmass often weathers more rapidly than the phenocrysts, leaving the latter in more or less strong relief.

Granitoid texture. — Those igneous rocks which are composed entirely of recognizable minerals of approximately the same size possess granitoid or even-granular texture. The individual minerals seldom exhibit definite crystal boundaries. Example, normal granite.

According to the size of mineral grains, we may recognize: (1) *Fine-grained* rocks, average size of particles less than one millimeter; (2) *medium-grained,* between 1 and 5 millimeters; and (3) *coarse-grained,* greater than 5 millimeters.

Other things equal, fine-grained granitoid rocks are more durable than coarse-grained ones.

PLATE IV, FIG. 1. — Banded felsite, showing flow structure.

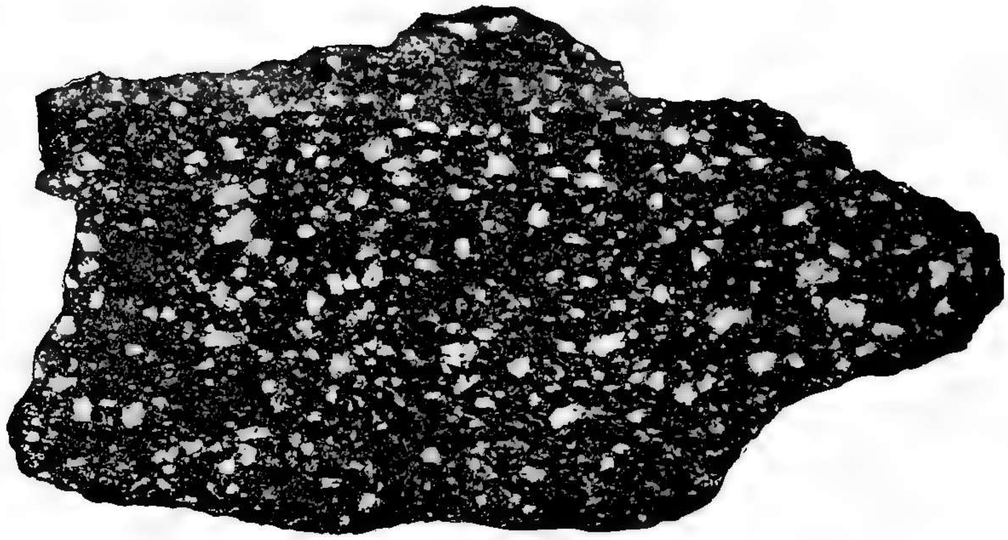

FIG. 2. — Trachyte, showing porphyritic texture.

Fragmental texture. — Fragmental is a textural term used in describing volcanic tuffs and breccias, which represent the consolidation of pyroclastic materials of all sizes erupted by volcanoes.

Porous texture. — The effusive igneous rocks, showing glassy and felsitic textures, may vary texturally from very compact and dense to very porous, with nearly all gradations between these extremes observed. According to the abundance of spacings or cavities, caused by escaping vapors from the magma during cooling, the rock may be termed *vesicular* (Plate V, Fig. 1), *scoriaceous*, or *pumiceous*.

When these cavities have been filled with mineral matter deposited from solution, the rock is described as having *amygdaloidal texture.* The fillings, which may be any one or more of a variety of minerals, usually zeolites, calcite, epidote, quartz, or feldspar, are termed *amygdules*, because of their resemblance to almond-shaped forms. Amygdaloidal texture is especially common in the surface lava flows (basalts) of all ages occurring in the United States.

During the cooling of granitoid (plutonic) rocks, irregular small cavities are sometimes developed, especially in some granites, into which the minerals project as well-formed crystals. These cavities are called *miarolitic.*

Differentiation of Igneous Rocks

It is a matter of common observation that magmas of different composition have been erupted not only from different vents, but from the same vent at different periods of time. This was formerly explained by some that at an unknown depth beneath the surface of the earth, there existed two layers of unlike magma, one lighter and more acid, the other heavier and more basic, and that the eruptions came from one or the other of these or a mixture of both. From the observed facts in the field it is now recognized that this assumption is inadequate as an explanation.

Plutonic igneous masses, such as granite stocks, etc., exposed now at the surface through erosion, frequently show a somewhat zoned arrangement; an outer margin of irregular width and extent whose mineral composition is essentially different from that of the larger central mass. That is to say, a border zone consisting of a greater concentration of the more basic, and sometimes the more acid, minerals than in the central mass. The two parts of the igneous mass usually contain the same minerals, but in different concentrations, and the passage from one to the other is frequently gradual.

A similar zonal arrangement has been observed in some laccoliths. Also similar evidence is afforded from the study of *complementary dikes.* Dikes composed of unlike mineral composition, one set light in color and density, and therefore acid in character; the other dark in color, heavier, and of basic character, have been observed cutting the rocks of a given area and closely associated. If this series of unlike dike material were sampled in proportion to their volumes and carefully analyzed, the bulk sample would reproduce the composition of the original parent magma. Such a system of dikes is termed *complementary.*