PETROGRAPHY

An Introduction to the Study of Rocks in Thin Sections

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PREFACE

THIS BOOK is concerned more with the description of rocks than with problems of genesis, more with petrography than with the broader field of petrology. Considerable space is devoted, nevertheless, to the mode of origin of igneous and metamorphic rocks, and even more is given to discussion of how sedimentary rocks are formed. We have assumed that the reader has already learned how to identify rocks by means of the hand lens, and is already acquainted with the principles of optical mineralogy. If he has this background, the present subject matter may be covered adequately by a year's course of six hours' laboratory work a week; indeed, by proper selection of rock types, the student may obtain a satisfactory basis of thin-section petrography within a semester.

Previous texts of this nature seem to us to devote too little attention to sedimentary rocks. This is regrettable, for most students of geology now enter the petroleum industry, where problems of sedimentation are of paramount importance. Lack of space, however, has made it necessary to omit all account of the study of sediments by oil-immersion methods, and to concentrate on the much-neglected examination of these rocks in thin sections.

Experience has taught us that in describing igneous rocks it is best to begin with fine-grained varieties that are obviously of magmatic origin, and then to consider their coarser-grained equivalents, the origin of some of which is still in doubt. And it has seemed proper to us to reverse the customary order of treatment by discussing first the basic igneous rocks and last the coarse-grained siliceous ones, some of which appear to bear the imprint of a metamorphic origin. Emphasis is placed, accordingly, on the transitional character of many igneous and metamorphic phenomena.

No new rock names have been coined; we have striven, on the contrary, to reduce the list as much as possible. Admittedly, some rather rare rocks have been allotted as much space as common rocks; but the reader should recall that it usually takes as long to describe one rock as another, and rare varieties often call for lengthier account than common ones. In brief, the abundance of a rock is not to be measured by the length of its description.

Most students like to see rocks neatly arranged in tables and charts because these provide simple aids to memory. We have included a few such aids, but we feel that "pigeonhole classifications" tend to give false ideas of exactitude. Our aim throughout has been to lay stress on the gradational nature of all rock series and on the arbitrary character of all groupings. And because verbal descriptions of rocks are often difficult to assimilate, we have provided abundant illustrations. About half of the rocks that we have figured are from the United States, but we have chosen as many examples as possible from other regions, particularly Europe. To conserve space for these illustrations, we have omitted all references to specialist publications not readily available to many students. We have also dispensed with lists of localities where particular rocks may be found. On the other hand, we have included a list of widely known works in which such information is available.

For various reasons this has not been an easy book to write; we hope that it will not be difficult to read. The preparation of an introductory text of any kind presents particular difficulties; especially troublesome are the problems of classification and of what to include and what to omit. Few instructors will agree as to the naming and grouping of rocks, the order in which they should be taken up, or the emphasis with which they should be described; each will be guided by his own predilections and the demands of his classes.

Responsibility for authorship is as follows: Part One, "Igneous Rocks," Williams; Part Two, "Metamorphic Rocks," Turner; Part Three, "Sedimentary Rocks," Gilbert. All microdrawings were made by Williams, except Figure 130, by Professor C. O. Hutton, and Figure 113, by Mr. R. S. Creely.

We are indebted to the following for loan or gift of specimens for illustration: Professor J. H. Taylor for a suite of English sedimentary iron ores; Professor Adolph Knopf for lamprophyres from the Spanish Peaks, Colorado; Professor Robert Compton for charnockites from Sweden; Professor C. E. Tilley and Dr. S. Agrell for much British and Scandinavian material; Professor H. H. Read and Dr. Walter Pitcher for metamorphic rocks from Scotland and Ireland; Professor H. H. Hess for Triassic diabases from New Jersey; Professor R. T. Prider for leucitic rocks from Western Australia; Professor Peter Misch for specimens from China and the Himalayas; Professor Bruno Sander for metamorphic rocks from the Austrian Alps; and Professor W. H. Mathews for sedimentary rocks from Canada.

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PART ONE

IGNEOUS ROCKS

1 Introduction

Origin of Igneous Rocks

Igneous rocks are formed by cooling and solidification of *magma*—that is to say, of hot, mobile rock matter made up wholly or in appreciable part of a liquid phase having the composition of a silicate melt. A magma may contain a gas phase, or it may consist almost wholly of solid, crystalline phases. Metamorphic rocks, on the other hand, form in the absence of a silicate melt by recrystallization and reaction between minerals that are solid though at high temperature. Exchange of ions between minerals and migrating fluid phases (usually aqueous gases or solutions) may change the mineral and chemical composition as well as the texture of solid rocks, and this transformation may take place over a wide range of temperature and pressure. Alterations of this kind are termed *metasomatic*. In the deeper levels of the earth's crust, igneous and metamorphic phenomena merge imperceptibly; hence many rocks originating there present transitional features. Among such rocks are the *migmatites*.

Now there can be no doubt that most volcanic rocks are produced from magmas that were largely liquid. But the origin of many deep-seated, plutonic rocks is problematical. Some rocks of this kind appear to have been formed by intrusion of mobile rock material that was only to a very minor extent liquid at the time of emplacement. It is doubtful, for example, whether many granites, other than those found in sills, dikes, and small stocks, were ever entirely or even largely liquid. Some geologists think that most of those that form batholiths in the cores of fold mountains are metasomatic in origin, the result of "granitization" of pre-existing rocks. Other geologists believe that they probably developed by selective melting of the roots of fold mountains built mainly from thick piles of geosynclinal sediments. But even if these hypotheses are valid, these batholithic granites must be classed as igneous because their intrusive relations prove that they were once permeated by a liquid phase, abundant enough to impart the mobility requisite for intrusion.

It is well known that, among volcanic rocks, basalts and basic andesites greatly preponderate over other types; and that, among plutonic rocks, on the other hand, granites and granodiorites are far more plentiful than all others combined. This fact has led to the view that volcanic and most plutonic rocks originate from two different *primary magmas,* even though their compositional range is almost precisely the same. According to this concept, volcanic rocks and the closely related intrusive rocks forming sills, dikes, ring dikes, cone sheets, lopoliths, and laccoliths are derived from a primary basaltic magma, supplied from deep-seated shells of basaltic material beneath the continents and oceans or formed by partial fusion of ultrabasic material at even greater depths. The plutonic rocks of batholiths and related intrusions, however, are confined to the continents, and most of them are thought, by holders of this view, to have been derived from a primary granitic magma produced by differential melting of the lower parts of the sialic crust. Some geologists go a step farther, postulating two kinds of primary basaltic magma, one a world-encircling shell of simatic (olivine) basalt, which by various processes has given rise to alkaline lavas such as trachyte and phonolite, and the other a subsialic (tholeiitic) basalt, supposedly found only beneath the continents and perhaps produced by contamination of the simatic basalt in contact with the base of the sial. This subsialic basalt is said to give rise in turn to calcalkaline lavas like andesite, dacite, and rhyolite. It must be stressed, however, that these are no more than working hypotheses meriting fair trial. Recent studies, indeed, suggest that tholeiitic basalts are not confined to the continents but occur also in mid-ocean, as in the Hawaiian Islands. Two other primary magmas have been proposed—namely, the anorthositic, derived from the basic portion of the continental crust, and the peridotitic, derived from a world-encircling shell beneath the basaltic ones. The great anorthosite intrusions, mostly of pre-Cambrian age, are thought to have been derived from the former, and the huge sills of serpentinite common in many fold mountains from the latter.

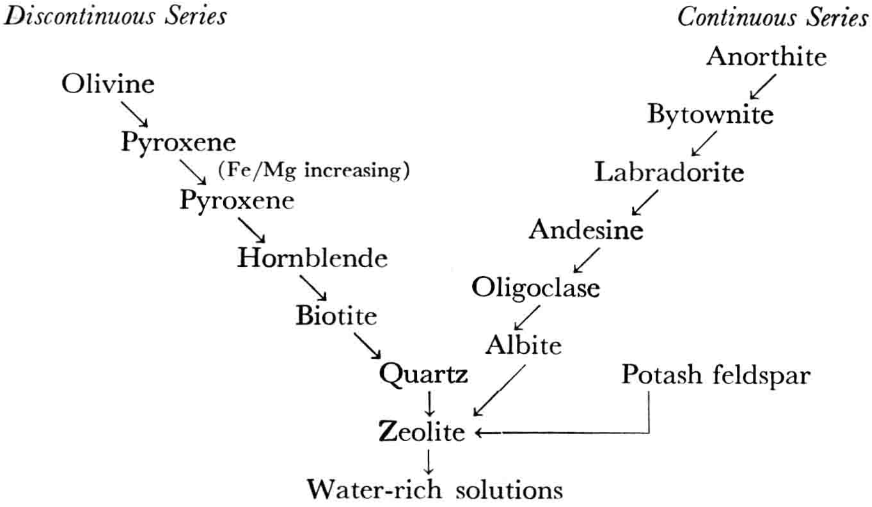
Because further discussion of these views is beyond the scope of this book, the reader is referred to the texts listed on page 385.

Magmatic Evolution

Primary magmas may be modified in composition to generate a great variety of igneous rocks. Let us now consider three ways by which this modification is effected.

Differentiation

This is a process whereby initially homogeneous magma splits into fractions of different composition. Conceivably it might result from *migration of ions or "molecules"* within liquid magma as a consequence of temperature gradients; but this mechanism is probably of little importance. A homogeneous melt might divide into two or more *immiscible fractions;* but this mechanism also, save in the rare case of sulphide melts, has been shown by laboratory experiments on silicate melts to be unimportant in the formation of igneous rocks. Another means of differentiation is *gaseous transfer.* Rising bubbles of gas may collect and transport slightly volatile constituents of magma from one place to another. But far more important than any of the three processes just mentioned is the *fractionation of magma resulting from crystallization.* Certain minerals in igneous rocks are normally associated because they crystallize at about the same temperature. Olivine and labradorite are typical associates; so are quartz and fayalite; so are orthoclase and oligoclase. Some pairs of minerals, on the other hand, are seldom seen together; among these are olivine and albite, and muscovite and labradorite. These relationships imply fractional crystallization of cooling magma. As crystallization proceeds, there is always a tendency for equilibrium to be maintained between the solid and liquid phases. To maintain this equilibrium as the temperature drops, early crystals react with the liquid and change in composition. The reaction may be progressive, so that a continuous series of homogeneous solid solutions is produced. In the case of the plagioclase feldspars, for instance, the first-formed crystals are those richest in lime; as reaction goes on and the temperature falls, the crystals become progressively more sodic. Changes of this kind constitute *continuous reaction series.* Certain ferromagnesian minerals, on the other hand, as cooling and reaction continue, are transformed at definite temperatures into other minerals, of different crystal structure. Olivine, for example, may be transformed into hypersthene, or augite into hornblende. Such abrupt changes constitute *discontinuous reaction series.* The diagram below, mainly after Barth's modification of Bowen's original diagram, shows the two principal reaction series.



Early, high-temperature members of both series generally crystallize together. That is why rocks like gabbro, which contain olivine and magnesian pyroxenes, usually contain calcic feldspars. Low-temperature minerals likewise tend to go together, so that mica, alkali feldspars, and quartz are closely associated in such rocks as granite. For the same reason certain minerals tend to be antipathetic; thus quartz and bytownite, and orthoclase and labradorite, are seldom seen side by side.

When reaction between crystals and liquid goes to completion, the minerals of the final rock are obviously not those that formed first but precisely the opposite ones. But if reaction is incomplete, because of too rapid cooling or for other reasons, early members of both reaction series may persist as relics in the final rock. That is why one observes zoned feldspars and crystals of one ferromagnesian mineral enveloped by shells of another.

Now when we consider the two reaction series listed above, certain variations must be borne in mind. Each ferromagnesian member of the discontinuous series has isomorphous varieties, among which those rich in magnesia precede those rich in iron in the normal order of formation. The magnesia-rich olivine, forsterite, usually forms at the same time as lime-rich plagioclase, while crystallization of iron-rich olivine, fayalite, is generally delayed until quartz and orthoclase are being precipitated. Other factors modify the normal sequence. The time when amphiboles and micas appear is affected by the ever-changing concentration of volatiles in the magma. Much depends also on differences in degree of fractionation in the two reaction series, for this influences the ratios between the various elements in the residual liquid. For example, the ratio of alkalies to silica plus alumina in the residual liquid is important in determining whether or not the rock will contain feldspathoids, such as nepheline, or iron-soda silicates, such as aegirite and riebeckite.

Fractionation of magma by crystallization is accentuated by the tendency of heavy minerals to sink and of light ones to float. *Crystal settling and crystal flotation* are therefore important in producing variation among igneous rocks. Concentration of olivine and calcic feldspars near the bottoms of thick sills and flows testifies to the settling of these early-formed crystals, just as abundance of leucite crystals among the first ejecta of some eruptions of Vesuvius testifies to upward flotation of that light mineral. An original basaltic magma in a volcanic reservoir may become crudely stratified by this process so that the kind of lava discharged depends partly on the volume extruded and partly on the level of the reservoir tapped by the eruptive conduit. *Gas streaming* is another process leading to differentiation, for bubbles may attach themselves to crystals and buoy them upward, or they may cause interstitial liquids to rise. Still another process is *filter-press action,* whereby the last residual liquids in a crystal mush are squeezed from one place to another in the magma chamber, or migrate into cracks cutting material that has already solidified. Such action results from continued upsurge of fresh magma, from opening of tension cracks in the walls of the reservoir, and from concurrent compression due to earth movements.

Assimilation

Evolution of magma may also be influenced by reaction with wall rocks. If magma has a temperature above that at which crystallization can begin, it may be contaminated by melting of the reservoir walls; it is not probable, however, that this condition is often realized, especially where plutonic magmas are involved. But consider a magma that has already begun to crystallize. Say that it has a granitic composition, that crystals of hornblende and oligoclase are already separating from the liquid, and that the wall rocks are gabbros composed essentially of augite and labradorite. Now labradorite is an earlier member of the continuous reaction series than oligoclase, and augite is an earlier member of the discontinuous series than hornblende. The magma cannot dissolve either the labradorite or the augite, for it is already effectively supersaturated with respect to them. What happens instead is a complex reaction whereby these foreign minerals are made over into hornblende and oligoclase, minerals which are in equilibrium with the liquid at that particular time. Consider next a hotter magma from which magnesian olivine is crystallizing, and say that the wall rocks again include crystals of augite, a later member of the discontinuous reaction series. Under these conditions the augite is actually dissolved by the magma; and, to supply the requisite latent heat of fusion, an equivalent amount of olivine is precipitated from the liquid. What kind of assimilation takes place will then depend on what minerals constitute the wall rocks and on what minerals are crystallizing from the adjacent magma. In any event the magma is contaminated, and the rocks ultimately formed from it are of hybrid origin. Such hybrid rocks are particularly common near the margins of large plutonic bodies. Some diorites, for instance, originate in this way by reaction of granitic magma with walls of gabbro or limestone.

Mingling of Magmas

Hybrid rocks, particularly volcanic and shallow intrusive rocks, may also be produced by mixing of partly crystallized magmas. Suggestive evidence comes from the close association within individual lava flows of plagioclase phenocrysts of widely different composition, many of which seem to be out of equilibrium with the groundmass. Examples occur in the San Juan volcanic province of Colorado, where basalts, andesites, and rhyolites were erupted in quick succession from the same or adjacent vents; other examples have been noted in volcanic rocks in Japan and California, where rhyolites containing zoned plagioclase phenocrysts with lime-rich cores are closely associated with basalts in which the zoned feldspars have soda-rich cores. Certain andesitic lavas of Hakone volcano, Japan, exhibit reverse zoning of both plagioclase and pyroxene phenocrysts: the rims of the plagioclase are more calcic than the cores, and the rims of the pyroxene contain more magnesia and less iron than the cores. Such abnormal phenocrysts might be incorporated in lavas by incomplete assimilation of wall rocks, but their wide and uniform distribution in many flows is more likely the result of mingling of different magmas before extrusion. Certain welded tuffs in Costa Rica consist chiefly of minute particles of glass whose notably different refractive indices denote a wide range in composition; and the glowing-avalanche deposits of the Valley of Ten Thousand Smokes, Alaska, consist of a mixture of white rhyolite pumice and dark, andesite scoria produced by effervescence of fresh magmas. Intimate admixtures of this kind suggest the simultaneous eruption of heterogeneous melts.

Stages of Consolidation of Magma

The first minerals to form from magma are usually anhydrous, for they develop at high temperature in melts containing only a small proportion of volatile (hyperfusible or fugitive) constituents. Such minerals are termed *pyrogenetic*. Their formation leads to relative enrichment of the residual liquid in volatile components and hence to later formation of hydroxyl-bearing minerals like the amphiboles and micas, which are termed *hydatogenetic*.

No clear separation can be made between the successive stages of consolidation of magma. Many names have been coined for these stages, but there is little agreement as to how they should be applied. In general, however, the first stage, during which only pyrogenetic minerals are formed, is referred to as the *orthomagmatic stage*. Some writers also include in this stage the period of crystallization during which hydroxyl-bearing minerals of low water-content develop. Subsequently, at temperatures of approximately 600–800° centigrade, magma enters the *pegmatitic stage*, during most of which liquid (silicate melt), crystalline, and gas (aqueous) phases coexist. Still later comes the *pneumatolytic stage*, when temperatures are approximately 400–600° C. and there is equilibrium between crystals and gas. Finally comes the *hydrothermal stage*, at temperatures of about 100–400° C., during which equilibrium is maintained between crystals, aqueous solutions, and aqueous gas.

During the final stages of consolidation of magma the volatile-rich residual solutions may induce widespread alterations, so that preexisting minerals are veined or replaced by new ones. Such altera-