IGNEOUS MINERALS AND ROCKS

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PREFACE

As a result of several years of teaching and research in petrology, I have perceived the increasing need for a book which will serve the ordinary requirements of a beginning student in microscopic igneous petrography, and, at the same time, will lend itself conveniently to use by more advanced students who frequently or occasionally wish to classify igneous rocks by microscopic methods. It is assumed that the student has had some training in the theory and techniques of optical crystallography. The task of writing such a book is a difficult one, for at the present time the nomenclatures of both minerals and igneous rocks are undergoing extensive scrutiny and revision and are in a state of flux. Moreover, the task of collecting and arranging the data scattered through the very extensive literature of mineralogy and petrography is in itself almost enough to deter any ambitions to produce a reasonably complete and accurate summary which could be contained between the covers of a single volume.

Changes in mineral and rock nomenclature that have been widely adopted generally consist of refinements in definitions of species and the introduction of definitive quantitative data. The trend is particularly noticeable in the field of mineralogy where the X-ray technique together with precision quantitative chemical analyses and refined measurements of physical properties has lead to a new concept of the basis for mineral classification. The classification of igneous rocks also has been improved by the introduction of the quantitative element.

But petrographers have not extended the warm reception to the proposed changes in rock nomenclature that has been accorded many of the new proposals in the field of mineralogy. The reasons for this are fairly obvious. Revisions of rock classifications often call for the coining of a host of new names and the abandonment of many old well-established names. It is difficult to displace, reorganize, or redefine terms which have been used with fair consistency in geological literature over a period of many many years. Also petrographers who have had extensive field experience with igneous rocks are disturbed by newly proposed rigidly quantitative rock classifications which require minute mathematical subdivision of rocks into species. Many petrographers have had the experience of studying rock masses consisting of many gradational but closely related rock types and having an average composition which may be expressed by one or two well-known and understood rock names. Consider the plight of the investigator who discovers that the rock body he is studying consists of ten different rock types if he classifies the rocks according to a rigid quantitative system, or consists of only one or two general types of rock if he uses a more flexible semiquantitative scheme. Certain of the modern quantitative systems require that the existing mass of rock names be modified to fit the system. In the author's opinion, a quantitative system should be made to accord as nearly as possible with the existing rock names and should preserve the meanings of the rock names as originally defined to as great an extent as possible.

Igneous-rock bodies, especially the larger ones, generally show variations in chemical and mineral composition from one portion to another. The crystalline rocks are aggregates of minerals, and the petrographer may gain some comfort from the fact that he can estimate very closely, if necessary, the composition of each mineral component. But, without the most exacting measurements, it is not easy to estimate the composition of many common rock-making minerals to a degree of accuracy consistent with the rigid quantitative subdivision of some of the modern rock classifications. Moreover, great care in determining the relative volumes of the minerals in a thin section may introduce a quantitative element which gives the investigator a certain feeling of security. But, all too often, the thin section is an inadequate sample of the rock being studied and actually gives only a qualitative estimate of the true average composition of the rock. This is especially true of the coarse-grained rocks.

In this book I have used several terms which have been criticized as inappropriate, meaningless, or ineffectual. If a petrographic term has been used widely and has a meaning which is well established through long, even though initially unjustified, usage, it has been retained, or at least mentioned, since it is not the purpose of this book to alter greatly, but only to record and summarize. An example is the use of the word "dense" as applied to aphanitic rocks. Although "dense" does not imply to the petrographer what it implies to the physicist, it is still a useful term established by continued consistent usage. The terms "acidic" and "basic" are in the same category, and, although I prefer "felsic" and "mafic," I do not feel that I should ignore or condemn the use of "acidic" and "basic," especially when it is considered that these terms have been used repeatedly and consistently in petrographic literature.

The rock classification used in this book is not rigidly quantitative but, rather, semiquantitative. It involves features of several individually proposed classifications. It is hoped that the arrangement is flexible enough to meet the needs of the field petrographer and, at the same time, definitive enough to permit the easy unequivocal determination of a rock name by microscopic studies in the laboratory.

At one stage in the preparation of the manuscript I considered the possibility of preparing a glossary of petrographic terms, but this idea was abandoned in the belief that a complete and detailed index with text-page references would serve the same purpose and would considerably reduce the size of the book.

I am constantly aware of my debt of gratitude to my many friends and colleagues who by counsel and discussion have helped to formulate and crystallize the opinions and convictions herein set down. Also, I cannot adequately express my feelings for the constant encouragement given me by my wife and coworker, Kathryn Kemp Wahlstrom, without whose assistance the manuscript could not have been completed.

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CONTENTS

PART I

IGNEOUS MINERALS

CHAPTER PAGE

I. INTRODUCTION 3

II. OPTICAL EXAMINATION OF ROCK-MAKING MINERALS 9

III. SUPPLEMENTARY METHODS FOR EXAMINING MINERALS IN IGNEOUS ROCKS 34

IV. MINERALS IN IGNEOUS ROCKS 47

V. TABLES FOR MINERAL IDENTIFICATION 142

PART II

IGNEOUS ROCKS

VI. GEOLOGICAL OCCURRENCE OF IGNEOUS ROCKS 191

VII. STRUCTURE, TEXTURE, COLOR, AND ALTERATIONS 201

VIII. CHEMICAL COMPOSITION AND CLASSIFICATION 226

IX. MINERAL COMPOSITION AND CLASSIFICATION 249

X. DESCRIPTIONS OF IGNEOUS ROCKS 268

XI. THE MICROSCOPIC IDENTIFICATION OF IGNEOUS ROCKS 339

INDEX 351

PART I

IGNEOUS MINERALS

CHAPTER I

INTRODUCTION

DEFINITIONS

Petrography is the branch of earth science which is concerned with the description and classification of rocks as they are examined in field exposures, in hand specimens, in thin sections, or as they are analyzed by qualitative or quantitative chemical procedures. Lithology is more restricted in meaning and is the megascopic study of rocks, generally in hand specimens. Descriptive petrology is synonymous with petrography.

Petrology is the science which is concerned not only with the description and classification of rocks but also with their origin and natural history. Thus petrology is regarded as embracing the fields of petrography and petrogenesis.

Rocks are naturally occurring aggregates of one or more minerals, or are partly or completely glassy or amorphous substances which, had they developed under proper conditions, would have crystallized into mineral aggregates. Minerals are naturally formed substances, either organic or inorganic, which have chemical compositions varying between arbitrarily set limits, and definitive physical properties.

CLASSES OF ROCKS

For the purpose of estimating the composition of the outer layers of the earth it is convenient to refer the data to a zone 10 miles deep. This zone is called the "10-mile crust," although it is fully understood that the crust, if such exists, is probably much thicker. Rocks naturally fall into three classes: the igneous rocks, the sedimentary rocks, and the metamorphic rocks. The igneous rocks were once in a molten condition and formed by the solidification of magma. The sedimentary rocks are secondary and form by the transportation and disposition of waste materials or dissolved substances derived from older rocks. Metamorphic rocks result from the partial or complete recrystallization of sedimentary or igneous rocks which have been subjected to the action of applied heat and/or pressure, and/or thermal solutions. If the metamorphic rocks are regarded as either meta-igneous or meta-sedimentary and grouped as required with either the igneous or sedimentary rocks, computations of the composition of the 10-mile crust give the values shown in Table 1.

TABLE 1

PREDOMINANT ROCK TYPES IN LITHOSPHERE, COMPOSITION FOR 10-MILE CRUST *

Igneous and meta-igneous rocks		95%
Sedimentary and meta-sedimentary rocks		5%
Shale	4 %	
Sandstone	0.75%	
Limestone	0.25%	

* *U. S. Geol. Survey, Professional Paper* 127, 1924.

COMPOSITION OF THE EARTH'S CRUST

Clarke and Washington[1] have estimated the average chemical composition of the 10-mile crust. Their estimates, which include not only the solid portion of the crust, the lithosphere, but the atmosphere and hydrosphere as well, are shown in Table 2. It should be noted

TABLE 2

AVERAGE COMPOSITION OF 10-MILE CRUST *

Including Lithosphere, Atmosphere, and Hydrosphere

	Per Cent		Per Cent
Oxygen	49.52	Manganese	0.08
Silicon	25.75	Sulfur	0.048
Aluminum	7.51	Barium	0.047
Iron	4.70	Chromium	0.033
Calcium	3.39	Nitrogen	0.030
Sodium	2.64	Fluorine	0.027
Potassium	2.40	Zirconium	0.023
Magnesium	1.94	Nickel	0.018
Hydrogen	0.88	Strontium	0.017
Titanium	0.58	Vanadium	0.016
Chlorine	0.188	Cerium; Yttrium	0.014
Phosphorus	0.12	Copper	0.010
Carbon	0.087	Inclusive	0.032
			100.000

* From F. W. Clarke and H. S. Washington, *U. S. Geol. Survey, Professional Paper* 127, 1924.

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[1] F. W. Clarke and H. S. Washington, *U. S. Geol. Survey, Professional Paper* 127, 1924.

that ten elements, oxygen, silicon, aluminum, iron, calcium, sodium, potassium, magnesium, hydrogen, and titanium, constitute more than 99 per cent of the crust by weight. Oxygen and silicon are by far the most abundant elements, and, accordingly, it is easily understood why the study of rocks is to a large extent a study of aggregates of silicate minerals. The truth of this statement is demonstrated by an examination of Table 3 which shows the average mineral composition of the igneous rocks in the 10-mile crust. Table 4 gives the average chemical composition in oxides of the igneous rocks. Again the importance of silica is apparent.

TABLE 3

AVERAGE MINERAL COMPOSITION OF IGNEOUS ROCKS *

	Per Cent
Quartz	12.0
Feldspars	59.5
Pyroxene and hornblende	16.8
Mica	3.8
Others	7.9
	100.0

* *U. S. Geol. Survey, Professional Paper* 127, 1924.

TABLE 4

AVERAGE CHEMICAL COMPOSITION OF IGNEOUS ROCKS *

	Per Cent		Per Cent
SiO_2	59.12	F	0.030
Al_2O_3	15.34	S	0.052
Fe_2O_3	3.08	$(Ce, Y)_2O_3$	0.020
FeO	3.80	Cr_2O_3	0.055
MgO	3.49	V_2O_3	0.026
CaO	5.08	MnO	0.124
Na_2O	3.84	NiO	0.025
K_2O	3.13	BaO	0.055
H_2O+	1.15	SrO	0.022
CO_2	0.102	Li_2O	0.007
TiO_2	1.050	Cu	0.010
ZrO_2	0.039	Zn	0.004
P_2O_5	0.299	Pb	0.002
Cl	0.048		100.000

* *U. S. Geol. Survey, Professional Paper* 127, 1924.

The most comprehensive computation of chemical analyses of igneous rocks is found in Professional Paper 99 of the U. S. Geological Survey, published in 1917. In this monumental work H. S. Washington tabulated virtually all of the published rock analyses that had appeared in the world literature from 1884 to 1913, inclusive. Richardson and Sneesby [2] made a statistical study of Washington's tables and by means of a diagram showed the variation of the silica content with the frequency of appearance of analyses for each silica content from 0 to 100 per cent. Their diagram is shown in Fig. 1 and emphasizes the fact that two rock types predominate—one with a silica content of about 52.5 per cent, corresponding fairly closely to the silica content of average basalt, and the other with a silica content of about 73 per cent, corresponding approximately to the silica content of average granite. Thus it has been demonstrated statistically that basalt and granite stand out as the two major types of igneous rocks. Moreover, the diagram indicates that most of the other rock types lie between basalt and granite insofar as the silica content is concerned. Approximately the same results would be obtained if frequency curves for the other oxide constituents of the igneous rocks were similarly plotted.

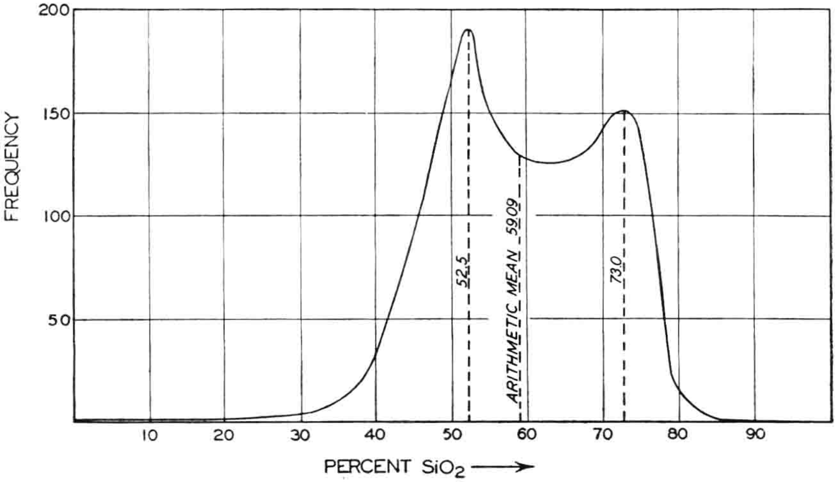

FIG. 1. Frequency distribution of silica in analyses collected by Washington in *U. S. Geol. Survey, Professional Paper* 99 (after Richardson and Sneesby, *Mineralogical Mag.*, vol. 19, 1922).

GEOLOGIC OCCURRENCE AND ORIGIN OF IGNEOUS ROCKS

The laboratory or field classification of an igneous rock should not be regarded as an end in itself. Rocks should be considered as samples of geologic bodies and should be studied as such. The petrographer

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[2] W. A. Richardson and G. Sneesby, "The Frequency Distribution of Igneous Rocks," *Mineralogical Mag.*, vol. 19, 1922, pp. 303–13.

constantly should keep in mind the fact that the examination of a rock should help to provide information leading to the correct interpretation of the origin and natural history of the structure of the larger geologic unit of which the rock is a component part. A knowledge of the geologic occurrence of a rock is as important as the mere classification of the rock based on a determination of the texture and mineral components.

As the science of petrology advances, it becomes increasingly apparent that certain igneous rocks crystallize in environments that might just as well have led to the development of metamorphic rocks. In other words the petrographer is at times faced with the problem of deciding whether a rock should be classified as igneous or metamorphic. Also, abundant evidence is at hand to indicate that certain rocks, granite for example, may form by the deep recrystallization of metamorphic rocks under the influence of high temperatures and tenuous liquid solutions. The rocks formed by these processes resemble in every detail those which have formed by direct crystallization of magma.

Physical–chemical research dealing with the crystallization characteristics of various silicate melts has yielded much information leading to the proper interpretation of many features seen in hand specimens and thin sections, and, with increasing knowledge, the study of rocks becomes more interpretive than descriptive. For example, the sequence of crystallization of a rock is, in general, more reliably determined by the application of well-known physical–chemical principles than by a simple inspection of the apparent order of crystallization as revealed by partial and completely developed crystals.

The writer, then, urges the student to regard samples of rock as more than just uninteresting specimens lying on the table or in the drawers of a dusty laboratory. The rocks should be studied so as to broaden the field of knowledge which leads to the eventual discovery of the minute and consecutive details of earth history.

METHODS OF STUDY

A student of petrography should, if possible, make an attempt to get the complete story of each rock sample. Under ideal conditions this would start with the examination and systematic sampling of rock masses in the field. Frequently a study of field exposures yields information that is invaluable in the laboratory study of hand specimens and thin sections. For example, the structures and textures as revealed in the field may be interpreted easily in large exposures where the origin and the geological relationships are apparent. But these same features in hand specimen or thin section may be puzzling and may present insurmountable problems. In general, the smaller the sample is, the more difficult is the interpretation of the genesis of the rock.

It is necessary at times to regard rock samples as mere aggregates of minerals which may be classified according to some more or less arbitrary scheme. This is true where, because of necessity, the student must study only hand specimens and thin sections. But, if it is not practical to study the field exposures of a rock, the student should make every effort to examine published maps and reports describing the areas in which the rocks occur. By this procedure petrographic studies assume real significance, and petrography takes its proper place as a handmaiden of petrology.

CHAPTER II

OPTICAL EXAMINATION OF ROCK-MAKING MINERALS

INTRODUCTION

The outstanding technique for the study of rocks makes use of thin sections or slices. Thin sections are useful not only for the determination of the mineral content but also for the observation of the internal structure, size, shape, and mutual relationships of the mineral grains. Moreover, if a thin section is well made, the mineral plates in the section are of uniform thickness, and each plate is cut in a certain fixed position with respect to its optical directions. If several grains of a mineral are present, the chances are excellent that some of the grains are oriented so as to permit accurate measurement of optical properties. Thin sections are almost indispensable for making studies of the order of crystallization of minerals and for making quantitative planimetric measurements of the mineral content.

For mineral identification the immersion technique has many advantages over the thin-section technique. Optical constants may be measured rapidly and accurately, and, in general, sufficient information may be obtained quickly to determine the mineral species. A fragment in a liquid immersion medium may be rolled into any desired position or transferred from one liquid to another, thus permitting the measurement of all optical properties in a single grain. The powder of a mineral used for optical measurements in liquids is in a condition suitable for making supplemental tests to confirm the optical identification. Also the act of crushing expedites the recognition of features such as fracture and cleavage. These features may not be obvious in thin section.

The immersion technique may be used to identify minerals broken from the hand specimen of a rock, but it does not permit the microscopic examination of the textural and structural features. For a careful petrographic examination of a rock, then, it is best to employ both the immersion and thin-section techniques, and one should be used to supplement the other.

The experience that comes from the careful comparison of minerals and textural features as seen in hand specimen with those seen under the microscope is invaluable in the development of the student's ability to work intelligently with rock exposures in the field.

It is the purpose of this chapter briefly to describe the features of rock minerals which may be observed in thin sections or liquid immersions of mineral fragments and to discuss the methods for the measurement of optical properties for the identification of the minerals.

PHYSICAL PROPERTIES OF MINERALS IN THIN SECTIONS

General Statement

Under favorable conditions all or many of the following characteristics of nonopaque minerals may be determined by inspection in thin sections: crystallization, habit, fracture, cleavage, color, twinning, zoning, relief, interference color, and whether the mineral is isotropic or anisotropic. The presence of inclusions and alterations also may be noted. By estimation or measurement the following optical properties may be ascertained: birefringence, refractive indices, extinction angles, optic orientation, optic angle, optic sign, dispersion, and sign of elongation or flattening. Opaque minerals may be identified in thin section but not so successfully as in polished sections or in grains plucked from the rock by hand or isolated in heavy mineral or magnetic separations.

Crystallization and Habit

Minerals such as spinel, zircon, apatite, and garnet generally are present in crystals sufficiently small and well-developed to permit identification of crystal forms and crystal system. Other substances such as quartz, feldspar, and nephelite may show outlines which are helpful in the establishment of the system of crystallization; but it should be remembered that, although a thin section has some thickness, the outlines of large crystals are random planar sections. The outlines of a crystal plate, then, may be very misleading unless they are used with caution. It is instructive not only to observe the outline of the crystal section but also to examine the attitude of the contacts of crystal faces with the surrounding minerals. This is most conveniently done by using the high-power objective of the microscope.

Crystal habit is an expression of the shape commonly shown by crystals of a certain mineral. Habits commonly seen in thin section are equant (equidimensional), tabular, platy or micaceous, elongate or prismatic, fibrous, lathlike, and microlitic. Mineral grains in thin sections show all degrees of perfection of crystal outline. *Anhedral grains* possess no crystal faces, *subhedral grains* have partially developed crystal faces, and *euhedral grains* have fully developed crystal faces and form self-contained complete crystals.

Structure in Minerals

Structure, as applied to minerals, refers to the manner in which the component parts or various portions of a crystal, or mineral grain, are related to each other. A single grain may show differences in composition from one part to another, or one part may be oriented differently from another. Inclusions or alterations also may produce characteristic structures.

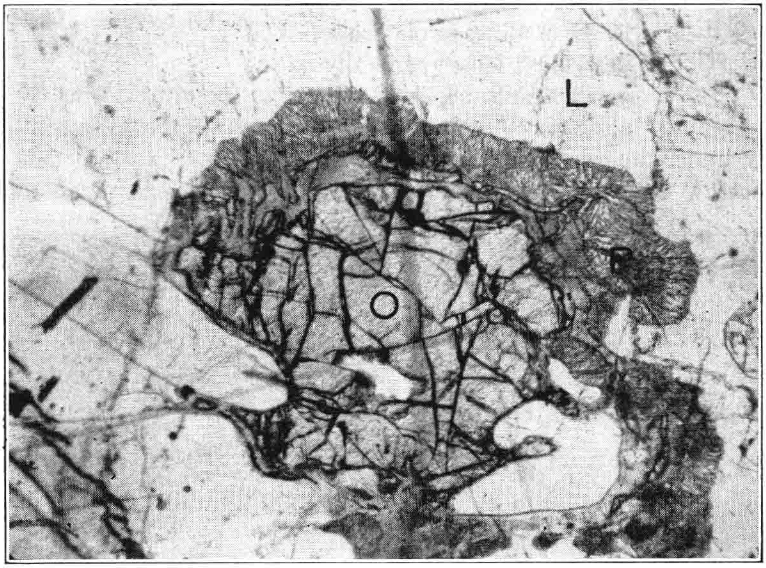

FIG. 1. Corona or reaction rim of vermicular pyroxene, *P*, along contact of olivine, *O*, with labradorite, *L*. Plain light.

Coronas (Fig. 1) are produced by the reaction between magma and early formed crystals or between adjacent minerals in contact, and are characterized by rims or zones containing radiating mineral aggregates differing in composition from the original mineral. An example is a rim consisting of pyroxene, amphibole, garnet, and the like, surrounding olivine grains in certain mafic rocks where the olivine is in contact with calcic plagioclase. Coronas are sometimes called *reaction rims* or *kelyphitic rims.* But many writers prefer to use the term "kelyphitic rim" for reaction rims around garnets.