

## PETROLOGY OF THE IGNEOUS ROCKS

while secondary quartz is liberated as a result of alteration of several species of rock-forming minerals.

In the following account, the primary essential minerals of igneous rocks are described first in as much detail as the writers consider necessary for the proper understanding of the igneous rocks in relation to their mineral composition. Particular attention is therefore paid to the internal structure of these minerals, as it is this which controls variation arising from atomic substitution within each 'family' of minerals.

The more important secondary minerals and the accessories also receive attention, but their treatment is necessarily selective.

As it is not our intention to attempt to compete with standard textbooks on mineralogy, much detail concerning the physical properties of the minerals has been omitted: such detail, if required, can be readily obtained from one of the standard works of reference.

### (2) Considerations concerning Atomic Structure

In these chapters the description of most groups of the rock-forming minerals is based on their atomic structure, as revealed by X-ray analysis. The actual technique involved in the latter, and the interpretation of the experimental data are matters for specialists; but the results of their researches are most illuminating to the student of mineralogy, particularly as regards the chemical relationships between allied mineral species and the interdependence between physical characters and the intimate internal atomic structure. We have of necessity drawn largely upon W. L. Bragg's invaluable account of the atomic structure of minerals. One great difficulty arises in connection with using the results of X-ray analysis: it is far from easy to make a useful illustration representing an intricate atomic design in three dimensions. Those which we have introduced must be regarded only as diagrams—they are only first approximations to the truth; but as a teaching device they have their place, if for no other reason than that they help to make sense out of the otherwise meaningless string of symbols which represents the chemical composition of any one of these minerals.

The component atoms or groups of atoms are held together by electrical forces of attraction between oppositely charged bodies of minute size. Those carrying a positive charge are termed **cations**; those with a negative charge are **anions**. For the sake of simplicity we may speak of the size of an atom, meaning the atomic radius, which is the distance, measured in Ångström units, at which mutual repulsion sets in when two atoms approach one another.

In the essential minerals of igneous rocks we are dealing largely with silicates, *i.e.* combinations of silicon (Si) with oxygen (O), these being associated with cations in variety. Those commonly

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converted into ferruginous pseudomorphs, particularly in basalts weathered under aeolian conditions. In lamprophyres, and occasionally in other rocks, the pseudomorphs may consist largely of carbonate, with or without some form of silica such as opal, chalcedony, or quartz-mosaic. Probably the most carefully studied pseudomorphs after olivine are those occurring in the Markle-type basalts in Scotland. They consist of penninitic chlorite, about 66 per cent, haematite, 32 per cent and 2 per cent of quartz.<sup>1</sup>

### PYROXENES

The pyroxenes constitute one of the most important groups of rock-forming silicates. Compared with the olivines, they contain a higher proportion of silica to the bases present, and are thus *meta-silicates*. In different members of the group the elements iron, magnesium, calcium and sodium are present in widely varying proportions, together with smaller amounts of aluminium, manganese, and titanium.

#### Atomic Structure and Chemical Relationships

The study of the X-ray structure of the pyroxenes has shown that the fundamental  $\text{SiO}_4$ -tetrahedra are linked together vertically into

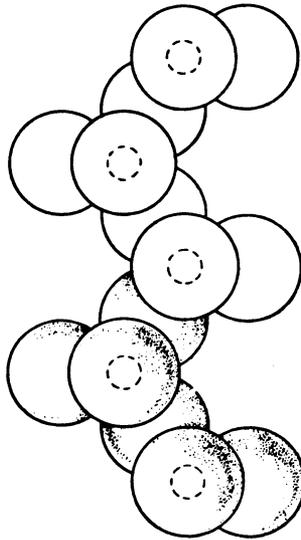


FIG. 7

Part of a chain of  $\text{SiO}_4$ -tetrahedra, as in pyroxenes. The unit of pattern contains ( $\text{Si}_2\text{O}_6$ ) shown shaded. Si-atoms shown by broken circles; large circles are O-atoms.

<sup>1</sup> Smith, W. W., *Min. Mag.*, 32 (1959), 324.

tional triangle of Fig. 10; actually the compositions of natural specimens lie a little below this line and are gradational into the augites—an arbitrary division between the two series must therefore be drawn, and we follow H. H. Hess in selecting  $Wo_{45}$  as the critical composition. This is the least amount of the wollastonite component that diopside may contain.<sup>1</sup>

The Mg-rich members of the series are by far the commonest. Diopside itself is essentially a metamorphic mineral; but diopsidic augite is not uncommon in igneous rocks including some pegmatites. Chrome-diopside and the closely related chrome-augite may be considered together: as the names imply, these clinopyroxenes only differ from diopside and augite in containing a small quantity of  $Cr_2O_3$ , which results in a rich green colour both in hand-specimens and thin sections. These minerals are of very limited distribution in igneous rocks, being restricted to certain ultramafites.

**Hedenbergite** is characteristic of metamorphic, rather than igneous rocks; but ferrohedenbergite, intermediate in composition between hedenbergite and ferrosilite, is quite common in granophyres, for example, forming part of the Skaergaard Complex in Greenland<sup>2</sup> and similar products of extreme differentiation by fractional crystallization. Ferrohedenbergite may be regarded as the lowest temperature member of the crystal fractionation series: augite—ferro-augite—ferrohedenbergite.<sup>3</sup>

### The Optical Characters of the Clinopyroxenes

The optic axial plane coincides with the single crystallographic plane of symmetry, parallel to (010) in the clinopyroxenes (Fig. 12), except in some pigeonites in which it is at right-angles to that plane. It follows, therefore, that the maximum extinction angle can be measured in (010) sections. These angles vary with composition and provide an easy means of checking the identity of the various clinopyroxenes as indicated in Fig. 13. The angles indicated in the left top corners of the 'fans' to the left of the middle line are measured between the cleavage traces and the slow vibration, Z. The complementary angles, between the fast vibration direction, X, and the cleavage traces are obtained by subtraction from  $90^\circ$ . The results would be anomalous if the nature of the vibration under test (whether fast or slow) were ignored; and further, it is only the *maximum* angle that is diagnostic. A section parallel to the front pinacoid (100) of augite extinguishes straight (*i.e.* extinction angle,

<sup>1</sup> Hess, H. H., Pyroxenes of the common mafic magmas. *Amer. Min.*, **26** (1941), 515–35; also *Amer. Min.*, **34** (1949), 621.

<sup>2</sup> Wager, L. R. and Deer, W. A., Petrology of the Skaergaard Intrusion, *Medd. om Grønland*, **105**, No. 4 (1939), 209.

<sup>3</sup> See for example Brown, G. M., Pyroxenes from the early and middle stages of fractionation of the Skaergaard magma. *Min. Mag.*, **31** (1957), 511.

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cleavage traces is the fast vibration, but with the latter it is the slow direction.

### Problems of Specific Identification of Amphiboles

It will be appreciated from the foregoing account that several amphiboles are of extremely complex composition. In this connection it is significant that virtually all the chemical components of a Basic igneous rock can, in certain circumstances, become incorporated in a single metamorphic amphibole. With so many variables (due to atomic substitution) it has proved impossible to devise a wholly satisfactory scheme of classification of the amphiboles, and it is impossible to represent the variations in chemical composition on a simple two-dimensional diagram. It follows that it is also impossible to construct a diagram correlating variation in chemical composition with optical properties. The accurate measurement of a single optical parameter, such as refractive index or optic axial angle, can provide a reasonable indication of the composition of, say, an olivine or a plagioclase in which only one variable ratio is involved—Mg/Fe in the former and Na/Ca in the latter; but this technique is impossible in the case of the amphiboles because there are too many variables. Particular optical properties vary widely in different specimens of any one species, with consequent overlap. It would appear from published data that no one chemical characteristic or optical property is diagnostic of a particular amphibole. This must not be taken to mean that optical characters are valueless; but when dealing with strongly coloured amphiboles, particularly brown ones, optical tests prove inadequate and recourse must be made to detailed chemical analysis. Formerly this was impracticable for reasons of time, facilities and cost; but now it is common practice to separate an amphibole from its matrix and submit it to detailed chemical analysis in the course of petrological research.

### Characters of Individual Species of Amphiboles

As a matter of convenience we propose to consider firstly the green amphiboles, then the brown ones. This enables us to deal with certain aspects collectively, for purposes of comparison and contrast.

It is appropriate to start with **common hornblende** which we use to illustrate the very extensive atomic substitution which is characteristic of the amphiboles. In the general formula the *X*-position may be occupied by  $\text{Ca}^{2+}$ ,  $\text{Na}^+$  and  $\text{K}^+$  in order of abundance; the *Y*-cations may include,  $\text{Mg}^{2+}$ ,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ , and  $\text{Al}^{3+}$ ; while in the *Z*-position we find  $\text{Si}_6$  together with  $(\text{Si}, \text{Al})_2$  bringing the total number of 'Z-cations' up to the required total of 8. Note the 'proxy- $\text{Al}^{3+}$ ' which substitutes for Si to a limited extent, in spite of the difference in valency. Consequently the total charge on 'Z' is