THE AMERICAN MINERALOGIST, VOL. 45, JULY-AUGUST, 1960

DIFFERENTIATION OF A LAMPROPHYRE SILL, NORTHERN LA PLATA MOUNTAINS, COLORADO

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ABSTRACT

Differentiation trends in a lamprophyre sill in the northern La Plata Mountains, Colorado, indicate fractional crystallization of an originally sodic melt containing pyroxene phenocrysts and inclusions of amphibolitic rock. Injection and fairly rapid crystallization caused the abundance of pyroxene to remain approximately constant throughout the sill. Fractional crystallization, however, resulted in an increase in the amount of plagioclase toward the center of the sill and a concurrent increase in albite content of the plagioclase. Selectively greater resorption of the amphibolite inclusions toward the center of the sill caused the percentage of hornblende to decrease inward from the margins, for the hornblende in the sill has been derived entirely from digestion of the inclusions and was out of equilibrium with the melt. Extensive late-stage activity involved formation of chlorite, argillization of plagioclase, and development of minor calcite and thomsonite.

INTRODUCTION

Studies of differentiation trends have been of prime importance in igneous petrology. For example, a current major controversy concerns the question of whether or not granitic rocks have solidified from differentiates of basaltic magma, and the answer to this problem depends partly on understanding the course of basaltic differentiation. In this connection, the evolution of the large and varied group of rocks known as the lamprophyres is a problem intimately related to the question of magmatic differentiation trends. The lamprophyres, with their generally mafic phenocrysts and alkalic groundmass, are not explainable by most standard differentiation mechanisms, and their origin is uncertain. The present study of the differentiation trends within one large lamprophyre sill has been made in the hope that the data presented here will contribute to a general understanding of the origin of lamprophyres.

The sill studied is in the northeastern part of the La Plata quadrangle, La Plata Mountains, southwestern Colorado. It crops out along Indian Trail Ridge, and the lower contact is almost coincident with the 12,000 foot contour. The original extent of the sill is unknown, for the outcrop on Indian Trail Ridge is the only remnant. The sill is 130 feet thick throughout its entire present extent and is intruded conformably into flat-lying sandstones of the Morrison formation. Contact metamorphism of the sandstones is minor and appears only in a baked zone 1 to 2 feet wide. The sill had previously been studied briefly by Cross (1899) in his general survey of the La Plata quadrangle. He reported a distinct compositional and textural layering parallel to the contacts, and it was this evidence of differentiation which attracted the writers to the present study.

Basically the sill consists of phenocrysts of pyroxene (both orthopyroxene and augite) and hornblende in a highly altered groundmass of oligoclase. Pyroxene comprises 10 to 25 per cent of the sill, hornblende ranges from 0 to 30 per cent in different portions, plagioclase constitutes from 40 to 60 per cent, and magnetite averages about 10 per cent. The plagioclase has been thoroughly altered to unidentified clays, some of the hornblende has been altered to chlorite, and calcite and zeolites form small veinlets and amygdule(?) fillings scattered throughout the sill. Amphibolitic inclusions, largely hornblende and oligoclase, are abundant near the borders of the sill but are absent toward the center. The sill is best classified as a spessartite.

The origin of lamprophyres has long aroused speculation. The literature and dominant ideas concerning them up to 1936 have been summarized by Knopf (1936), and many of the questions which he posed still remain unanswered. Differentiation in an individual lamprophyre dike has been described by Campbell and Schenk (1950), but other evidence concerning variability within single intrusions is scarce.

Procedure

A total of 31 samples was collected at intervals of 1 to 5 feet from the upper to lower contact of the sill. Owing to steepness of slopes and lack of vegetation, the sill was well exposed through its entire thickness, and the only deterrent factor in the sampling was a small amount of talus cover.

One thin section was cut from each sample, and modal compositions were determined by point counting 1000 to 1300 points. Pyroxene compositions were determined with a universal stage by measuring the optic angles of 10 grains in each of 6 slides (spanning the complete thickness of the sill); measurements were made by the Berek method (Emmons, 1943, pp. 28–32), and some were checked by stereographic plotting of the optic axes. All grains were measured more than once. Plagioclase compositions were determined in 11 slides spaced at 10 foot intervals from the base to top of the sill. Very few of the plagioclase grains in any slide could be measured owing to the intense argillization, but in each of the 11 slides determinations were made on from 3 to 6 grains which clearly showed extinction positions of albite twins. The measurements were made on the universal stage by determining the maximum extinction angle to the (010) plane and estimating the relative relief. These measurements, which showed a small range in composition within each slide, were checked by refractive index measurements made by inserting index oils under the cover glass of the slide and into contact with an edge of the section from which the mounting medium had been removed. This method of index measurement has been described by Rogers (1960). Grain sizes of pyroxene, hornblende, and plagioclase were determined in selected slides by measuring the long axes of 10 grains of each mineral (only 3 hornblende grains in one slide) with a micrometer ocular.

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Pyroxene

Pyroxenes occur chiefly as phenocrysts and form large euhedral crystals throughout the entire sill (Fig. 1). Orthopyroxenes (highly magne-

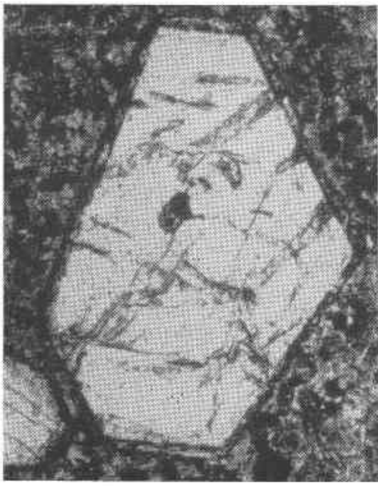


FIG. 1. (left) Euhedral orthopyroxene grain. Plain light, ×75.

FIG. 2. (right) Partially replaced hornblende grain with magnetite rim. Plain light, ×40.

sian) and augite are both present and appear to maintain a ratio of about 1 orthopyroxene to 1 augite throughout the sill.

The orthopyroxenes are generally optically positive, though a few grains of high 2V have a negative sign. Indices are less than 1.72, and optic angles range from about 55° to 90°. The pyroxenes, therefore, are in the high magnesian part of the series (based on data in Winchell and Winchell, 1951). Attempts to detect variation in pyroxene composition from place to place in the sill failed owing to variability of compositions in single slides; in one slide the optic angle ranged from 55° to 87° in different grains. Some of the grains are zoned, invariably with the core higher in magnesium content than the margins.

The augite grains are faintly pleochroic from colorless to pale green. They are optically positive and have average optic angles of about 62°.

Hornblende

Hornblende grains occur only as phenocrysts and generally form corroded, apparently highly altered crystals (Fig. 2). The corroded grains contrast strongly with the euhedral shape of the pyroxene and suggest that the hornblende was dissolving in the lamprophyric melt while the pyroxene was growing. The resorption of hornblende has been

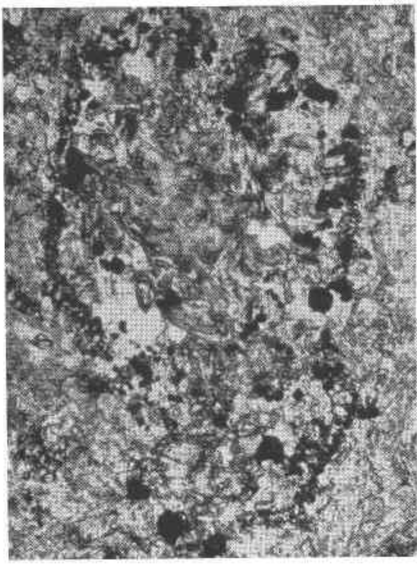



FIG. 3. (left) Magnetite grains outlining a pseudomorphously replaced hornblende grain. Plain light, ×45.
FIG. 4. (right) Schiller in hornblende. Plain light, ×195.

noted in other lavas from the general San Juan region by Larsen Jr. and Cross (1956, p. 262). Hornblende occurs only in the marginal portions of the sill, and in the center its place is occupied by amphibole-shaped pseudomorphs consisting of oligoclase, magnetite, and alteration products. Hornblende pseudomorphs are particularly marked by rims of small magnetite grains (Fig. 3). Some of the hornblende shows small-scale schiller structure (Fig. 4).

Optical properties of the hornblende are somewhat variable. The mineral is pleochroic from yellow green to greenish brown, has n_z (measured in index oils) of about 1.68, has an average extinction angle of 24° ($Z \wedge c$), and has an extremely high optic angle ($\pm 75°$–$90°$). The composition is apparently roughly intermediate between those of hastingsite and edenite with some iron content (based on data in Winchell and Winchell, 1951).

Plagioclase

Plagioclase forms a fine-grained groundmass of subhedral to anhedral, somewhat lath-shaped grains. Almost all grains are extensively altered to clay minerals, thus preventing detection of such features as zoning, twinning, etc. A few grains in each slide were sufficiently unaltered that albite twinning could be detected, and measurement of these grains in 11 of the slides placed plagioclase in the compositional range from An_{14} to An_{24}.

Magnetite

Magnetite forms small anhedral grains either scattered throughout the slides or in clusters around altered hornblende grains. The scattered magnetite may represent primary crystallization, whereas the clusters are certainly the products of reaction and alteration. Many of the individual grains, however, are of uncertain origin, and consequently no effort was made to separate the two types in the modal analysis.

Minor minerals

Apatite forms tiny euhedral crystals in the groundmass in many samples. Quartz is very rare but occurs in a few slides as rounded, undulant grains.

Secondary and alteration minerals

Chlorite occurs both in the groundmass and as an alteration product either rimming or completely replacing hornblende. Some of the slides contain nearly 20 per cent of chlorite or similar clay mineral.

Plagioclase is almost completely altered to clay minerals, though the exact nature of the clays is unknown.

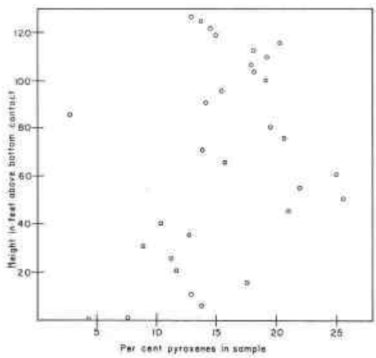
Calcite occurs in vein and cavity (amygdule ?) fillings and as an alteration product of hornblende. The zeolite thomsonite occurs in a few cavities.

Inclusions

Mafic inclusions, up to several inches in diameter, occur near the margins of the sill but are absent in the center. The rock comprising the inclusions is essentially an altered amphibolite consisting of greenish-brown hornblende (50 per cent) very similar to the hornblende grains in the sill, highly argillized oligoclase (35 per cent), and minor biotite, chlorite, magnetite, and calcite. The hornblende, oligoclase, and biotite are probably primary constituents, whereas the magnetite, chlorite, and calcite appear to represent reaction of the inclusions with the lamprophyric magma. The alteration of the hornblende is the same as in the sill rock, and some of the grains are rimmed with magnetite in the same fashion as hornblende in the sill. The distribution of the inclusions and the similarity of the hornblende grains in the sill and inclusions indicates that the hornblende in the sill has probably been derived by digestion of the inclusions.

Differentiation of the Sill

The various components of the sill are unevenly distributed, and their variations are shown diagrammatically in Figs. 5 to 10. Except for the



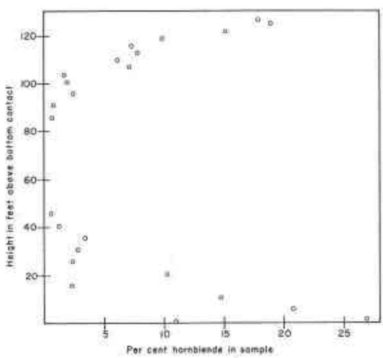


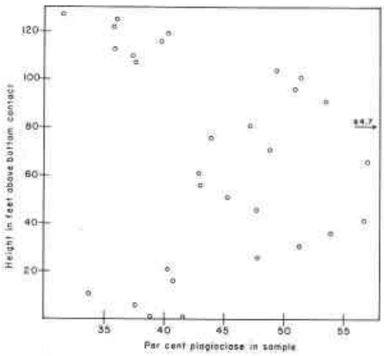
Fig. 5. Distribution of total pyroxenes in sill. The ratio of orthopyroxene to augite is about 1:1 and is roughly constant throughout the sill.

Fig. 6. Distribution of hornblende in sill.

magnetite, the distributions are symmetrical around the center of the sill and apparently indicate fractional crystallization of the lamprophyre from the edges inward.

Figure 5 shows that pyroxenes are rather uniformly distributed throughout the sill. One explanation for this uniformity, in view of the obvious variations shown by other minerals, is that the pyroxenes had nearly completed crystallization prior to injection of the magma into the sill. The pyroxene grains would then be thoroughly mixed with the melt and, having densities possibly very close to that of the residual melt, might not show appreciable gravitative settling. The failure of comparatively low-density mafic materials to settle is also indicated by the fact that amphibolitic inclusions are abundant near the upper margin of the sill as well as near the lower margin. A mixing such as proposed above could explain the variations in composition shown by pyroxene grains within individual thin sections if it is assumed that the magma injected to form the sill was derived from a partially differentiated body at depth.

Figure 6 shows the distribution of hornblende in the sill. In view of the textural evidence for the resorption of hornblende, the distribution is best explained by assuming increasing resorption toward the center of the sill, where the magma remained fluid for a longer period of time than at the margins. Abundant digested hornblende grains (as in Fig. 3) support this conclusion. Unfortunately, many clusters of magnetite and other alteration products in the central part of the sill do not have the



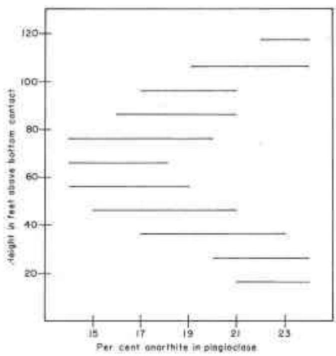


FIG. 7. Distribution of plagioclase in sill.
FIG. 8. Variation in composition of plagioclase in sill.

diagnostic hornblende outline and might be accounted for in other ways; consequently no quantitative estimate has been obtained for the abundance of completely resorbed hornblende.

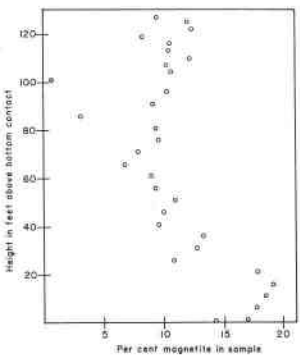
The abundance of plagioclase (Fig. 7) increases inward toward the center of the sill. Presumably the variation is caused by the fact that the sodic plagioclase is a late-crystallizing component and is thus concentrated in the residual liquids toward the center of the sill. This conclusion is supported by the increase in albite content of the plagioclase toward the center of the sill (Fig. 8).

Unlike hornblende and plagioclase, the magnetite is not symmetrically distributed in the sill (Fig. 9). The greater concentration toward the base of the sill may testify to some gravitative settling of the comparatively dense magnetite. The slight decrease in abundance from the upper contact to the center, however, indicates increased viscosity of the melt near the more rapidly cooled margins, thus preventing complete settling of the relatively early-crystallizing magnetite.

Figure 10 shows the distribution of grain sizes of pyroxene, hornblende, and plagioclase. As expected, the grain size of plagioclase increases inward toward the more slowly cooled center, whereas the size of the partially resorbed hornblende grains decreases inward. Pyroxenes appear to be larger near the upper margin of the sill than near the center and base, though the explanation for this variation is uncertain.

Conclusions

The variations in the sill described in the present paper probably resulted from the differentiation and fractional solidification of an injected melt originally containing abundant solid material. The pyroxenes may



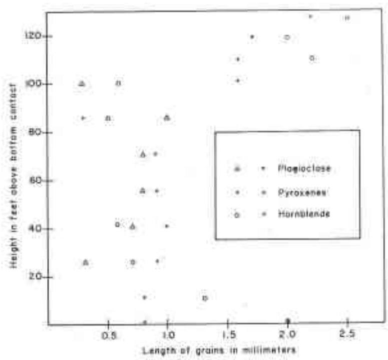


FIG. 9. Distribution of magnetite in sill.
FIG. 10. Variation in grain sizes of pyroxene, hornblende, and plagioclase in sill.

have been almost completely crystallized at the time of injection, and if the hornblende content of the sill can be attributed to digestion of amphibolite inclusions (as are found near the margins), then the total amount of solid material in the original injection was about 50 per cent. The amphibolitic rock fragments were probably part of the Archean basement and were caught in the lamprophyric magma as it was injected upward. After intrusion, the inclusions were ingested by the relatively high temperature magma, the hornblende grains were added to the melt, and the individual grains reacted with the magma and were partly pseudomorphously replaced. The plagioclase component was enriched in the residual fluids during the fractional crystallization, and both its total abundance and the percentage of albite in individual grains increased toward the center of the sill. Magnetite crystallized comparatively early and underwent minor gravitative settling. The abundance of volatiles either in the original magma or in the later phases is indicated by the chloritic alteration of the hornblende, the extreme argillization of the plagioclase, and the presence of calcite and zeolite in veins and patches throughout the sill.

The incorporation of inclusions containing oligoclase and somewhat sodic hornblende certainly increased the sodium content of the magma. The sodic nature of the lamprophyre, however, cannot be accounted for in this manner, as shown by the fact that the rock in the margins of the sill, where digestion of the inclusions has been negligible, contains a highly sodic plagioclase. The original magma before addition of the inclusions evidently consisted of pyroxene crystals in contact with a very sodic melt. The presence of resorbed hornblende, however, is of importance in view of Bowen's (1956, p. 269–273) conclusions that resorption of hornblende and/or biotite is an important process in the development of many lamprophyres.

Acknowledgments

Field work on this project was supported by a grant from the Arthur L. Lake Fund of the Department of Geology, The Rice Institute. The writers express their thanks to Mr. Ted H. Foss, Department of Geology, Lamar State College, Beaumont, Texas, for assistance in the field work.

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Manuscript received November 4, 1959.