1968

The Hornblende-Aegirine Augite Reaction Relationships of the Trunk Lake Granite, Maine

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THE HORNBLENDE-AEGIRINE AUGITE REACTION RELATIONSHIPS
OF THE TUNK LAKE GRANITE, MAINE

BY
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A Thesis
Submitted to the Faculty of Geology
at the University of North Dakota
in partial fulfillment of the requirements
for a Bachelor of Science Degree in Geology
May 28, 1968
ABSTRACT

Textural relationships indicate that the structure of aegirine augite controlled the secondary formation of hornblende in the Tunk Lake granite. In the marginal rocks of the granite body some grains of aegirine augite may be partially or completely enclosed by hornblende. Hornblende also replaces aegirine augite along fractures. Extensive replacement results in grains which have small cores of aegirine augite surrounded by hornblende. Cleavage patterns and optical orientations of the two minerals indicate that their c axes are parallel. Pyroxene can be transformed to hornblende by a minor shift in orientation of its basic tetrahedral structure. Chemical changes necessary in the transformation are the addition of water, a slight decrease in sodium and the substitution of some aluminum for silicon. The transformation of aegirine augite to hornblende was caused by an increase in magma water vapor pressure and a decrease in temperature.
ACKNOWLEDGMENTS

The writer would like to thank Dr. Frank R. Karner for his invaluable assistance and guidance in this study.
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INTRODUCTION

The Tunk Lake granite pluton is exposed over a circular area of 70 square miles in south eastern Maine. Its general location is shown on Figure 1. Karner (1968) has summarized the petrology of the pluton. The granite consists of six gradational zones containing rocks which form a continuous sequence from margin to core. Beginning with the chill zone they are:

- Zone I: Magnetite-aegirine augite granite
- Zone II: Hornblende-aegirine augite granite
- Zone III: Hornblende granite
- Zone IV: Hornblende-biotite granite
- Zone V: Biotite granite
- Zone VI: Biotite quartz monzonite

Quartz content, type of feldspar and mafic minerals present vary systematically in the six rock types.

The feldspars vary from sodium-rich microperthite in zone I to a sodium-deficient perthite and plagioclase in zone VI. Quartz decreases from 35 percent in the chill zone to 20 percent in zone II. It gradually increases again to 35 percent in the core of the pluton. The ferromagnesian minerals grade from aegirine augite through hornblende to biotite. Aegirine augite is most abundant in the marginal rocks, hornblende is prominent in zones II, III, and IV, and biotite is the primary mafic mineral in zones V and VI.

This study is concerned with the reaction relationships of hornblende and aegirine augite. Specimen numbers refer to locations given in Karner (1968, Appendix).
HORNBLENDE-AEGIRINE AUGITE RELATIONSHIPS

A detailed microscopic study was made to determine some of the textural, optical, and structural relationships of the aegirine augite and hornblende. Pertinent data regarding chemical and phase relationships of the two minerals were derived from the literature.

Distribution

Aegirine augite occurs throughout zones I and II and occasionally in the outer margins of zone III. It is often seen as cores in hornblende grains in the inner and outer margins of zones II and III respectively (Fig. 2, Plate 1). Hornblende is most abundant in zone III, however it is common in zones I through V. The grains in zones IV and V are often partially replaced by biotite (Fig. 3).

Textural Relationship

Aegirine augite grains are generally anhedral to subhedral and average 1-2 mm in diameter (Fig. 4, Plate 2).

Hornblende grains in zones I and II are usually anhedral to subhedral (Fig. 5, Plate 3). The grains of zones IV and V are progressively more euhedral towards the center of the pluton (Figs. 6 and 7, Plate 4). The average hornblende grain is 3-4 mm in diameter.

In zones II aegirine augite is often partially or completely replaced by hornblende. The hornblende may surround the aegirine augite as seen in Figure 2, or it may form
Plate 1. Hornblende with aegirine augite core, viewed with crossed nicols, X30. Hornblende is at extinction.

Figure 2. Hornblende with aegirine augite core. Shaded area is hornblende. Black areas are opaque minerals.
Figure 3. Typical hornblende grain from zone IV, being replaced by biotite. Black areas are opaque minerals.
Plate 2. Typical aegirine augite grains from zone I, plane polarized light, X30.

Figure 4. Typical aegirine augite grains from zone I. Shaded area is iron oxide.
Plate 3. Typical hornblende grains from zone I, viewed with plane polarized light, X30.

Figure 5. Typical hornblende grains from zone I.
Plate 4. Typical euhedral hornblende grain viewed with crossed nicols X30.
Figure 6. Typical euhedral hornblende grain with secondary biotite.
Figure 7. Euhedral hornblende grain with c axis perpendicular to the stage.
partial rims which inter-finger with the aegirine augite. Hornblende generally replaces the aegirine augite from the margin of the grain inward so that only a small core of the original mineral remains. The hornblende surrounding the augite core is one continuous grain. Hornblende replacing aegirine augite appears to assume the same general shape of the grain it is replacing. Replacement of aegirine augite along fractures by hornblende often results in small islands of aegirine augite separated from the original grain.

Sharp contacts between aegirine augite and hornblende grains indicate that there is little or no alteration zone between grains (Plate 1).

The similar shapes of the secondary hornblende and the primary aegirine augite suggests that the two grains may be similarly oriented.

Optical Relationship

Pleochroism in aegirine augite is very weak. Karner (1968, p. 207) has described it as X light green, Y light green, and Z greenish yellow. Most grains appear a very light green.

Pleochroism in hornblende is strong, and Karner (1968, p. 207) describes it as X yellow, Y yellow to brownish green, and Z light brown.

Due to the variation in pleochroism aegirine augite is usually quite distinct when included in a hornblende grain.

The aegirine augite in the Tunk Lake granite is optically positive, its average $2V = 68^\circ$, $Z:c = 72^\circ$ and Beta = $107^\circ30'$ (Karner, 1968, p. 207).
The hornblende in the Tunk Lake granite is optically negative, its average \(2V = 40^\circ\), \(Z: c = 30^\circ\), and \(\text{Beta} = 105^\circ\).

In Figure 8b the optic orientations of both aegirine augite and hornblende are superimposed on their crystallographic axes as seen in the (010) plane. Since both minerals are monoclinic their crystallographic axes are similar except for Beta. As Beta for hornblende and aegirine augite varies by only \(2^\circ 30'\) for the purpose of clarity only one set of axes has been drawn.

If the \(c\) axes of the two minerals are parallel to each other and perpendicular to the stage, aegirine augite should give an off-centered optic axis or BXO interference figure and hornblende should give an off-centered BXO or optic axis figure respectively.

Hornblende with its \(c\) axis perpendicular to the stage displays two cleavages intersecting at \(56^\circ\) and \(124^\circ\) (Plate 5).

Plate 5. Euhedral hornblende grain with \(c\) axis perpendicular to the stage, with plane polarized light, X75.
Figure 8a. Crystallographic orientation of a monoclinic mineral.

Figure 8b. Optic orientation of hornblende and aegirine augite superimposed on their crystallographic axes, viewed perpendicular to the (010) plane. \( a, b, \) and \( c \) are drawn as equal for both minerals.
Few grains with this orientation and containing aegirine augite cores are present in the thin sections observed. In those that are present the optical relationships described above can be seen. When a BXO figure is seen in hornblende an optic axis figure is seen in the aegirine augite. When an optic axis figure is seen in hornblende a BXO figure is seen in aegirine augite.

These optical figures indicate that the c axes of the two minerals observed are at least close to parallel. This further substantiates the possibility that hornblende replacing aegirine augite has the same orientation of the grain it is replacing.

To verify whether or not the two crystals have the same orientation several grains must be observed. Using a microscope with a universal stage the exact orientation of all 3 of the crystallographic axes could be determined. By observing several grains it could be determined if the hornblende is consistently in the same orientation with respect to its augite core. If the grains are in the same orientation it is feasible that the aegirine augite structure has controlled the orientation of the hornblende.

Structural Relationship

Cleavage

Fractures are prominent in aegirine augite (Fig. 9, Plate 6). They are present in hornblende but not as extensively as in aegirine augite.

Cleavage in hornblende is usually distinct (Fig. 5, Plate 3). Aegirine augite generally displays very poor
Plate 6. Typical aegirine augite grain from zone I, viewed with plane polarized light X30.

Figure 9. Typical aegirine augite grain from zone I showing faint lineations and conchoidal fractures.
cleavage (Fig. 9), however a vague lineation is usually present.

Occasionally cleavage is observable in both the aegirine augite core and the hornblende rim. When this occurs, if the grains' $c$ axes are horizontal, the cleavages of the two minerals are close to parallel. The angle between the two cleavages seldom exceeds $10^\circ$.

Some grains which first appear to be aegirine augite rimmed by hornblende, on close observation prove to be zoned hornblende (Plate 7). There seems to be a definite contact between the two regions and the inner zone is non pleochroic. However the cleavage is continuous throughout the whole grain and both zones have the same extinction angle.

Plate 7. Zoned hornblende grain viewed with plane polarized light, $X$ 30.
The similar trend of cleavage directions parallel to the c axes in combined grains of hornblende and aegirine augite is in accordance with the apparently similar orientation of the c axes of the grains.

Atomic Structure

Aegirine augite is a typical pyroxene consisting of silicon-oxygen tetrahedra, linked to form continuous chains of composition (SiO$_3$)$_n$ (Fig. 10A). These chains are linked laterally by the cations (Ca, Na, Mg, Fe, etc.) (Deer and others, 1963, p.2).

Hornblende, a typical amphibole, consists essentially of silicon or aluminum oxygen tetrahedra, linked to form continuous double chains of composition (Si$_4$O$_{11}$)$_n$ (Fig. 10B). These chains are linked by the cations (Mg, Fe, Al, Na, Ca, OH) (Deer and others, 1963, p. 202). One amphibole chain is exactly double the width of a pyroxene chain. The double chain can be considered a condensation of 2 single chains. In the pyroxene chain each silicon is sharing 2 oxygens while in the amphibole chain each silicon is sharing 3 oxygens.

Since the structures of both minerals are based on silicate chains it seems possible that as hornblende replaces aegirine augite it could form around the silicon-oxygen chains already present in the pyroxene structure. In so doing the hornblende would keep the same general shape and orientation already held by the aegirine augite. This would explain the apparent structural control evident in the transformation of aegirine augite to hornblende.

Before these assumptions can be proven a detailed comparison must be made of the atomic structures of aegirine augite and hornblende.
Figure 10. Chain structures of (A) pyroxenes and (B) amphiboles.

(A) Pyroxene (Single Chain) — (SiO$_3$)$_n$

(B) Amphibole (Double Chain) — (Si$_4$O$_{11}$)$_n$
Chemical Relationship

Karner (1968, p. 207) has estimated the following formulas for the aegirine augite and hornblende in the Tunk Lake granite.

Aegirine augite \((\text{Na}_{0.5}\text{Ca}_{0.5})(\text{Fe}^{0.35}\text{Fe}^{+3}\text{Fe}^{+2}\text{Mg}_{0.25}\text{Al}_{0.15})\text{Si}_{2}\text{O}_{6}\)

Hornblende \((\text{Na}_{2}\text{Ca}_{2}\text{Mg}\text{Fe}^{+2})(\text{Al}_{0.4}\text{Fe}_{0.4}\text{Al}_{0.4}\text{Ti}_{0.2})\text{Al}_{2}\text{Si}_{6}\text{O}_{22}(\text{OH},\text{F})_{2}\)

The formulas indicate that in the transformation of the augite to hornblende there is an increase in \(\text{SiO}_2\), a substitution of aluminum for silicon and an addition of hydroxyl, fluorine and titanium.

In Table 1 a comparison in the chemical composition of both minerals is made (Karner, personal communication). Due to the substitution of aluminum for silicon the percentage of \(\text{SiO}_2\) in hornblende decreases in relation to aegirine augite. From augite to hornblende there is an increase in ferrous iron and a decrease in ferric iron. The result is a total increase in iron of about 5 percent. There is a decrease in sodium. Water and titanium appear to be the only new constituents added in the reaction. A general equation for the reaction can be written

\[X \, Y \, \text{Si}_2\text{O}_6 + \text{Al}_2\text{O}_3 + \text{SiO}_2 + \text{H}_2\text{O} = X \, Y(\text{AlSi})_8\text{O}_{22}(\text{OH})_2\]

where \(X\) and \(Y\) are the cations present in each mineral.
Table 1. Chemical Composition of Aegirine augite and Hornblende

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Percent Aegirine augite</th>
<th>Percent Hornblende</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>52.9</td>
<td>38.0</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3.4</td>
<td>12.9</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>12.3</td>
<td>3.4</td>
</tr>
<tr>
<td>FeO</td>
<td>7.9</td>
<td>22.7</td>
</tr>
<tr>
<td>MgO</td>
<td>4.4</td>
<td>4.3</td>
</tr>
<tr>
<td>CaO</td>
<td>12.3</td>
<td>11.8</td>
</tr>
<tr>
<td>Na₂O</td>
<td>6.8</td>
<td>3.3</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

In the transformation of aegirine augite to hornblende the chemical composition is not significantly changed. Therefore, the alteration probably consists primarily of a change in position and orientation of the constituents already present in the pyroxene.

Phase Relationships

Yagi (1966) has shown that aegirine augite, consisting of 50 percent aegirine and 50 percent diopside at 1 atmosphere of pressure will begin to crystallize at 1100°C. However, impurities, such as ferrous iron and water vapor, lower freezing temperatures in granites by as much as 200°C (Deer and others, 1963, p. 294). Karner (1968, p. 207) estimates the aegirine augite of the Tunk Lake granite to
be about 50 percent aegirine and 50 percent diopside. It probably began to form at a temperature of roughly 800°C, the temperature Karner (1968, p. 210) estimates for emplacement of the pluton.

Phase relationships for hornblende similar to that found in the Tunk Lake granite have not been determined. Hornblende from the Tunk Lake granite has a hastingsite composition, and Appleman and others (1966, p. E-21) suggest that hastingsite should have pressure temperature conditions for stability similar to those of pargasite. Deer and others (1963, p. 294) state that iron-rich hornblendes are likely to have breakdown curves several hundred degrees lower than those of pargasite. Pargasite at 1000 bars vapor pressure begins to crystallize at about 800°C. Therefore, the hornblende in the Tunk Lake granite probably began to form at a temperature considerably lower than 800°C.

Pyroxenes develop in relatively dry environments while amphiboles require a water pressure of at least 1000 bars (Deer and others, 1963, p. 294). Boyd (1959) estimates that the minimum melting curve of a granite and an iron-rich hornblende-pyroxene reaction will be at 1000 bars pressure.

The water content of the Tunk Lake granite melt was initially low but increased substantially as the pluton froze (Karner, 1968, p. 210). It is likely that the primary aegirine augite became unstable with increasing vapor pressure. As the temperature in the granite dropped, hornblende, more stable at high vapor pressures, began replacing the unstable aegirine augite.
CONCLUSIONS

Primary aegirine augite crystallized initially in the Tunk Lake pluton. As the melt cooled and vapor pressure increased, conditions favoring hornblende were reached and aegirine augite was replaced by secondary hornblende.

There appears to be little change in chemical composition between the hornblende and aegirine augite. The transformation is thought by this writer to be primarily a reorientation of chemical constituents in the pyroxene accompanied by an addition of hydroxyl and aluminum and a loss of some sodium.

The apparent similar orientation of hornblende grains and their aegirine augite cores, suggest that the structure of the aegirine augite has controlled the secondary formation of the hornblende.
Figure 1. Location Map
REFERENCES CITED


