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# SIGNIFICANCE OF AMPHIBOLE PARAGENESIS IN THE BIDWELL BAR REGION, CALIFORNIA

Robert R. Compton, *Stanford University, Stanford, California.*

## Abstract

In the northwest Sierra Nevada, regionally extensive low-grade metabasaltic rocks containing abundant actinolite $[(\mathrm{Na,K})_{0.35}\mathrm{Ca}_{1.9}(\mathrm{Mg,Fe''})_{4.4}\mathrm{Al}_{0.4}(\mathrm{OH})_{1.6}\mathrm{Si}_{7.7}\mathrm{Al}_{0.3}\mathrm{O}_{22}]$ are converted to hornblendic rocks in the contact aureole of a small batholith. Hornblende in the outer part of the aureole is associated with oligoclase, epidote, and minor chlorite, and has the composition $(\mathrm{Na,K})_{0.35}\mathrm{Ca}_{1.7}(\mathrm{Mg,Fe''})_{4}(\mathrm{Fe''',Al})_{1.1}(\mathrm{OH})_{1.9}\mathrm{Si}_{6.7}\mathrm{Al}_{1.3}\mathrm{O}_{22}$, while hornblende in the inner part of the aureole is associated with andesine (and locally clinopyroxene), and has the composition $(\mathrm{Na,K})_{0.4}\mathrm{Ca}_{2}(\mathrm{Mg,Fe''})_{3.8}(\mathrm{Al,Fe'''})_{1.1}(\mathrm{OH})_{1.7}\mathrm{Si}_{6.7}\mathrm{Al}_{1.3}\mathrm{O}_{22}$. The abrupt conversion of actinolite to aluminous hornblende in the outer part of the aureole contrasts with gradational conversions in some regionally metamorphosed schists, and this contrast is probably caused largely by differences in the dehydration and reaction rates of the two environments. Ferrohastingsite $[(\mathrm{Na,K})_{0.8}\mathrm{Ca}_{2}(\mathrm{Fe'',Mg})_{3.8}(\mathrm{Fe''',Al})_{1}(\mathrm{OH,Cl})_{2.1}\mathrm{Si}_{6}\mathrm{Al}_{2}\mathrm{O}_{22}]$ formed in the inner part of the aureole from rocks (metatuffs) low in Si and high in Fe. Igneous hornblende that crystallized with biotite in the border zone of the batholith has the composition $(\mathrm{Na,K})_{0.5}\mathrm{Ca}_{1.9}(\mathrm{Mg,Fe''})_{4.4}(\mathrm{Fe''',Al})_{0.8}(\mathrm{OH})_{0.8}\mathrm{Si}_{7.1}\mathrm{Al}_{0.9}\mathrm{O}_{22}$.

## Introduction

Amphiboles are essential constituents of almost all of the abundant metavolcanic rocks of the northern Sierra Nevada, and also occur widely in granitic rocks that have been emplaced into this terrane. In general, the metamorphic amphiboles are products of two plutonic episodes, the first being low temperature dynamothermal metamorphism on a regional scale, and the second contact metamorphism by the granitic intrusions. Much of the igneous amphibole formed directly from the more mafic granitic magmas, but some is doubtless the result of contamination of acidic magmas by amphibole-rich metamorphic rocks. Because reactions involving amphiboles are very important in the evolution of the Sierran rocks, and because little is known about the exact nature of these minerals, pure amphibole samples were separated from five rocks that form a reasonably well known genetic series. The purposes of this paper are to present the chemical compositions and physical properties of these minerals and to consider the reactions involved in their formation, especially the conversion of actinolite to aluminous hornblende.

## Petrologic Basis of the Study

The general geologic setting of the Bidwell Bar region has been described elsewhere (Compton, 1955), and only the most necessary relations will be presented here. The region is an excellent one in which to explore the general amphibole evolution outlined above because almost all the metamorphic rocks have similar (basaltic) compositions, the relations between these rocks and a small granitic batholith are well exposed, and the contact metamorphic aureole around the batholith is distinct. Moreover, the aureole shows progressive variations of texture and mineralogy that indicate variation in metamorphic intensity, and it was mapped in two zones on the basis of textural criteria. The outer contact of the aureole was drawn where greenschists and greenstones give way (in a few hundred feet) to fine-grained tough hornfelses, and the contact between the outer hornfels zone and the inner zone of the aureole was drawn where metamorphic amphibole is clearly visible to the unaided eye. The contact between the batholith and the metamorphic rocks is generally sharp, but veins and nodes of tonalite occur widely in the inner zone of the aureole, some being intrusive and some metasomatic.

Although the aureole zones were not mapped on the basis of thin sections, the cartographic units can be correlated with gross petrographic variations. The dominant mineral assemblage outside the aureole is actinolite-albite-epidote-chlorite; in the outer zone of the aureole it is hornblende-oligoclase-epidote (locally with chlorite); and in the inner zone of the aureole it is hornblende-andesine (locally with clinopyroxene). The metasomatic veins in the inner zone generally consist of andesine or labradorite, hornblende, and quartz, while the intrusive veins consist of andesine or oligoclase, quartz, hornblende, and biotite.

The five analyzed amphiboles were chosen so as to give a picture of amphibole variation correlative with the critical changes in this paragenesis. One is from the low grade regional terrane, one from the outer zone of the aureole, two from the inner zone of the aureole, and one from an intrusive outlier of the batholith. The specimen from the regional terrane is a mafic greenstone that lies 6,000 feet outside the aureole. It is especially important to this study because a large part of the analyzed actinolite clearly pseudomorphs igneous clinopyroxene, while the same actinolite is abruptly overgrown here and there by thin rims of green metamorphic hornblende identical to that of the contact aureole. Thus two-stage amphibole reactions are well displayed, and the sharpness of the overgrowths of aluminous hornblende is important in the interpretation of the actinolite-hornblende reaction. The specimen is of further interest because it shows that partial contact metamorphism extended far beyond the mapped aureole.

The second amphibole is from a hornfels that lies near the middle of the outer zone of the aureole. The rock contains less epidote than most metabasaltic rocks of the outer zone; however, it was selected because the presence of chlorite suggested its amphibole might be intermediate between actinolite and the aluminous hornblendes of the inner zone, a suggestion that was not borne out by the chemical analysis.

The first of the two amphiboles from the inner zone was separated from an amphibolite that lies only 200 feet from the batholith, and is veined by tonalite that is probably metasomatic. The separation utilized only the amphibolite, although the hornblendes of amphibolite and veins are physically identical. Like several other amphibolites from the immediate contact zone, this rock contains small amounts of clinopyroxene, and it may well represent the most advanced stage of contact metamorphism.

The second amphibole from the inner zone is from a ferrohastingsite schist that is interbedded with andesine-hornblende amphibolites and biotite-quartz-hornblende-oligoclase schists about 2,500 feet from the batholith. It is of interest in this study because similar ferrohastingsites occur in several parts of the inner zone, and this mineral is the only unusual amphibole of the entire complex.

Finally, the hornblende separated from the mafic outlier of the batholith occurs only a few feet from a sharp intrusive contact with typical amphibolite of the inner zone. The abundance of hornblende at such contacts with amphibolites, and the heterogeneity of the border tonalites suggest that the hornblende of the tonalite might well have formed by contamination of a more acidic magma by amphibolite (Compton, 1955, p. 33–37). The purpose of the analysis was to determine the compositional differences between hornblende of the wall rock and hornblende of the new biotite-rich igneous assemblage.

## AMPHIBOLES

### *Separation*

The fractionations of the different constituents from the greenstone and the hornfels were complicated by the intricately interdigitated shapes of many of the minerals, yielding a large number of composite grains in all but the finest materials. This was overcome by using very well-sorted fractions of 0.01 to 0.03 mm. size, obtained by repeated decanting of −250 mesh material for settling periods of between 3 and 5 minutes. These well sorted samples responded well to centrifuging in heavy liquids, the principal separatory procedure used. The impurities were counted in all samples submitted for analysis, and in each case amounted to less than 0.5 per cent of the sample.

### *Compositions*

The chemical analyses are listed in Table 1. Analyses 2 and 3 are each the average of two analyses which differed only slightly from the amounts listed. The $H_2O^+$ determinations were made by the Penfield method, using an oxy-coal gas blast flame.

The numbers of atoms in the formulae of the amphiboles (Table 2)

TABLE 1. COMPOSITIONS AND PHYSICAL PROPERTIES OF FIVE AMPHIBOLES FROM THE BIDWELL BAR REGION, CALIFORNIA

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 53.41 | 45.33 | 45.87 | 38.04 | 47.80 |
| $Al_2O_3$ | 4.56 | 10.12 | 11.17 | 11.09 | 6.94 |
| $TiO_2$ | 0.37 | 0.54 | 0.57 | 0.87 | 0.80 |
| $Fe_2O_3$ | 0.83 | 5.51 | 4.82 | 7.38 | 4.98 |
| FeO | 9.70 | 14.61 | 9.72 | 21.30 | 9.65 |
| MnO | 0.25 | 0.59 | 0.25 | 0.36 | 0.38 |
| MgO | 15.09 | 10.00 | 11.69 | 4.00 | 14.58 |
| CaO | 12.52 | 10.53 | 12.62 | 11.99 | 12.19 |
| BaO | 0.10 | 0.02 | 0.03 | 0.10 | 0.06 |
| $Na_2O$ | 0.88 | 1.04 | 1.14 | 1.40 | 1.44 |
| $K_2O$ | 0.63 | 0.36 | 0.29 | 1.69 | 0.63 |
| $H_2O^+$ | 1.63 | 1.89 | 1.73 | 1.85 | 0.77 |
| $H_2O^-$ | 0.05 | 0.15 | 0.32 | 0.19 | 0.05 |
| F | 0.01 | 0.01 | 0.01 | 0.02 | 0.06 |
| Cl | n.d. | n.d. | n.d. | 0.66 | n.d. |
| $P_2O_5$ | 0.04 | 0.01 | 0.01 | 0.11 | 0.07 |
| Total | 100.07 | 100.71 | 100.24 | 101.05 | 100.40 |
| Less O for F and Cl | 0.01 | 0.01 | 0.01 | 0.16 | 0.03 |
| Total (corrected) | 100.06 | 100.70 | 100.23 | 100.89 | 100.37 |
| Specific gravity | 3.07–3.12 | 3.25–3.29 | 3.22–3.24 | 3.39–3.40 | 3.20–3.21 |
| $\alpha$ | 1.626 | 1.654 | 1.660 | 1.692 | 1.651 |
| $\gamma$ | 1.645 | 1.674 | 1.680 | 1.714 | 1.670 |
| $\gamma$-$\alpha$ | 0.019 | 0.020 | 0.020 | 0.022 | 0.019 |
| $2V_\alpha$ | 77–80° | 65–69° | 64–66° | 30–31° | 64–67° |
| $Z\wedge c$ | 15–18° | 16–18° | 20–21° | 15–17° | 16–18° |
| Orientation | Y=b | Y=b | Y=b | Y=b | Y=b |
| X | Colorless | Straw | Straw | Grayish yellow | Straw |
| Y | Very pale yellow-green | Olive | Olive | Deep olive | Olive |
| Z | Very pale green | Blue-green | Slightly bluish green | Deep greenish blue | Slightly bluish green |

1. Actinolite from mafic greenstone (BB-1-16). Bidwell Bar (7½′) quadrangle; lat. 39°36′12″ N., long. 121°27′39″ W.* Analyst, R. Klemen.
2. Hornblende from hornfelsed metadiabase (BB-4-171c). Bidwell Bar (7½′) quadrangle; lat. 39°33′03″ N., long. 121°25′50″ W. Analyst, R. Klemen.
3. Hornblende from clinopyroxene-bearing amphibolite (F-1-120b). Forbestown quadrangle; lat. 39°35′45″ N., long. 121°19′43″ W. Analyst, R. Klemen.
4. Ferrohastingsite from ferrohastingsite schist (CM-1-11). Clipper Mills quadrangle; lat. 39°35′38″ N., long. 121°14′26″ W. Analyst, R. Klemen (except that Cl determination was made by writer).
5. Hornblende from mafic tonalite (RRC-9). Bidwell Bar (7½′) quadrangle; lat. 39°32′54″ N., long. 121°25′06″ W. Analyst, R. Klemen.

* Note: to plot specimen localities on geologic map of area (Compton, 1955, plate 1), change all latitudes of map from 37° to 39°.

Table 2. Numbers of Atoms in Formulae of Amphiboles from the Bidwell Bar Region, California

| | | 1 | | 2 | | 3 | | 4 | | 5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (Z) | Si | 7.66 | 8.00 | 6.72 | 8.00 | 6.68 | 8.00 | 6.04 | 8.00 | 7.06 | 8.00 |
| | Al | 0.34 | | 1.28 | | 1.32 | | 1.96 | | 0.94 | |
| (Y) | Al | 0.43 | 0.56 | 0.48 | 1.11 | 0.61 | 1.20 | 0.10 | 1.07 | 0.25 | 0.89 |
| | Ti | 0.04 | | 0.06 | | 0.07 | | 0.09 | | 0.09 | |
| | Fe‴ | 0.09 | | 0.57 | | 0.52 | | 0.88 | | 0.55 | |
| (X) | Mg | 3.25 | 4.44 | 2.23 | 4.10 | 2.57 | 3.78 | 0.95 | 3.83 | 3.21 | 4.44 |
| | Fe″ | 1.16 | | 1.80 | | 1.18 | | 2.83 | | 1.18 | |
| | Mn | 0.03 | | 0.07 | | 0.03 | | 0.05 | | 0.05 | |
| (W) | Ca | 1.92 | 2.28 | 1.69 | 2.04 | 1.97 | 2.33 | 2.02 | 2.78 | 1.92 | 2.45 |
| | Ba | 0.01 | | 0.00 | | 0.00 | | 0.01 | | 0.00 | |
| | Na | 0.24 | | 0.28 | | 0.31 | | 0.42 | | 0.41 | |
| | K | 0.11 | | 0.07 | | 0.05 | | 0.33 | | 0.12 | |
| | OH | 1.56 | 1.56 | 1.89 | 1.89 | 1.69 | 1.70 | 1.96 | 2.14 | 0.76 | 0.79 |
| | Cl | n.d. | | n.d. | | n.d. | | 0.17 | | n.d. | |
| | F | 0.00 | | 0.00 | | 0.01 | | 0.01 | | 0.03 | |

were calculated on the basis of 24 (O,OH,F,Cl) (Warren, 1930, p. 504–516), and they are close to the values determined structurally by Warren, except that number 5 is distinctly low in the OH group and high in the total of the X and Y groups. The total positive charges of number 5 also are too high, and can be balanced only by assuming that the "vacant" OH positions are occupied by O ions; however, the rather low $Fe_2O_3$ does not support this possibility. If, on the other hand, it is assumed that the $H_2O^+$ determination is low, the composition can be recalculated so as to agree reasonably well with the ideal structural ratio of atoms. Since this possibility cannot be certain, however, the values in Table 2 are those calculated from the original analysis.

The impurities were calculated out of the analyses before the atomic compositions of the amphiboles were computed, but these corrections are so small that the only value improved by more than 0.01 of an atom is the Fe‴ of amphibole 2, which is decreased by 0.03 of an atom to correct for included magnetite.

### *Physical properties*

The principal physical properties of the analyzed amphiboles are given in Table 1. The range of specific gravity listed is that of the two heavy liquids in which the final mineral sample was separated from heavier and lighter materials. The amphiboles in rock specimens 3, 4, and 5 were so homogeneous that by far most of the monomineralic amphibole grains were included in the final sample. The amphiboles of specimens 1 and 2, on the other hand, were so heterogeneous that much monomineralic material had to be separated from the analyzed samples in order to free the samples from composite grains. Judging from the composition of these impure fractions, amphibole 1 is somewhat more dense and presumably a little richer in iron than the average actinolite of the rock, and amphibole 2 is distinctly more dense, more deeply colored, and probably contains more iron and aluminum than the average amphibole of the rock.

The indices of refraction were determined by the immersion method, using a sodium light source; all liquids were measured at once with a refractometer. The very fine-grained material submitted for analysis was used, and because the material was somewhat variable (note the specific gravity ranges) an error as large as 0.002 is possible for samples 3, 4, and 5, and an error as large as 0.003 for samples 1 and 2. The values for 2V and $Z \wedge c$ were determined in sodium light on the universal stage. The ranges listed include all values that recurred frequently in measurements of a number of grains, and this variation is likely to be caused at least in part by the compositional variations within each sample.

## PETROGRAPHY

The general petrography of the Bidwell Bar rocks has been described (Compton, 1955), and only the petrography of the rocks from which amphiboles were separated will be presented here. These rocks are in many respects representative of the other rocks with which they are associated; the greenstone, however, is considerably more mafic than the typical metabasaltic rocks of the regional terrane.

### *Mafic greenstone*

Amphibole 1 is from a non-schistose, actinolite-rich greenstone that originally contained abundant large phenocrysts of augite and calcic plagioclase, but now consists entirely of metamorphic minerals. The following approximate mode, in weight per cent, was computed from a count of 1,000 points:

| | | | |
|---|---|---|---|
| albite | 8.0 | chlorite | 4.0 |
| epidote | 26.0 | leucoxene | 5.0 |
| actinolite | 53.0 | calcite | 2.0 |
| hornblende | 2.0 | | |

An approximate chemical composition calculated from this mode is given in Table 3.

Actinolite occurs both as pseudomorphs after augite and as acicular

TABLE 3. CALCULATED CHEMICAL COMPOSITIONS OF AMPHIBOLE-BEARING ROCKS FROM THE BIDWELL BAR REGION, CALIFORNIA

| | 1 Mafic greenstone | 2 Hornfelsic metadiabase | 3 Amphibolite | 4 Ferrohastingsite schist | 5 Tonalite |
|---|---|---|---|---|---|
| $SiO_2$ | 46.3 | 49.3 | 49.2 | 37.9 | 59.5 |
| $Al_2O_3$ | 12.6 | 14.3 | 16.5 | 10.9 | 18.0 |
| $TiO_2$ | 2.0 | 1.1 | 1.7 | 1.6 | 0.5 |
| $Fe_2O_3$ | 3.4 | 6.0 | 3.0 | 7.2 | 1.8 |
| FeO | 7.1 | 9.0 | 6.2 | 20.6 | 3.8 |
| MnO | 0.2 | 0.3 | 0.1 | 0.4 | 0.1 |
| MgO | 8.9 | 6.7 | 7.1 | 3.8 | 4.1 |
| CaO | 14.0 | 8.6 | 11.6 | 12.3 | 5.9 |
| $Na_2O$ | 1.5 | 2.9 | 3.1 | 1.3 | 4.4 |
| $K_2O$ | 0.4 | 0.5 | 0.4 | 1.6 | 1.4 |
| $H_2O$ | 2.7 | 1.3 | 1.1 | 1.8 | 0.5 |
| Cl | — | — | — | 0.6 | — |
| $CO_2$ | 0.9 | — | — | — | — |

prisms intergrown with albite, chlorite, and epidote. Here and there the faintly colored actinolite is abruptly overgrown by small patches of a more deeply colored hornblende that is blue-green in Z, with $\gamma = 1.674$, $2V = 62°–68°$, and $Z \wedge c = 17°–18°$. These data indicate that it is identical with the hornblende of the contact aureole (see number 2, Table 1).

The original plagioclase grains are largely pseudomorphed by clusters of epidote and calcite. Most of the epidote is iron-rich, but some grains are zoned to iron-poor rims, and euhedral clinozoisite crystals occur in clusters associated with chlorite. The chlorite is optically positive, has a birefringence of 0.002, and a refractive index of approximately 1.580.

### *Hornfelsic metadiabase*

Amphibole 2 is from a fine-grained hornfelsed metadiabase that has the following mode, in per cent by weight:

| | | | |
|---|---|---|---|
| quartz | 1.5 | titaniferous ore | 5.0 |
| oligoclase (An$_{22}$) | 28.5 | chlorite | 0.4 |
| hornblende | 62.5 | apatite | 0.1 |
| epidote | 2.0 | | |

The point count runs used to compute this mode were unusually consistent, and therefore the calculated chemical composition in Table 3 should be quite reliable.

Most of the hornblende is in small rather deeply colored prisms that interfinger with feldspar in a randomly oriented hornfelsic fabric. Some larger (0.5 mm.) grains have lighter colored cores that grade abruptly out to the deeper hornblende of the prisms. The cores probably represent large actinolites from the original metadiabase that were not completely reacted to aluminous hornblende; it is also possible, though less likely, that they are iron-poor aluminous hornblende. It is the more deeply colored hornblende that was analyzed.

Chlorite occurs here and there with the aluminous hornblende, but its genetic relation to the amphibole could not be determined. Epidote is iron-poor and is commonly included in oligoclase. Rather large skeletal ore grains are scattered evenly through the rock.

### *Clinopyroxene-bearing amphibolite*

Amphibole 3 is from a typical amphibolite of the inner zone, characteristically veined and spotted by mafic tonalite. Judging from the consistency of point counts, the following mode (measured on amphibolite only) should be quite reliable:

| | | | |
|---|---|---|---|
| andesine ($An_{38}$) | 36.0 | magnetite | 0.1 |
| hornblende | 60.0 | apatite | 0.3 |
| clinopyroxene | 0.3 | zircon | tr. |
| sphene | 3.3 | alkali feldspar and zeolite | tr. |

The texture is granoblastic but the hornblende shows a moderate degree of crystallographic orientation, *c* and {100} tending to lie in a plane. The hornblende is evenly colored and free of inclusions. Clinopyroxene was detected only in crushed samples of the rock; however, judging from its textural relations in other sectioned rocks, it is granular, as coarse-grained as the hornblende, and shows no obvious reaction relation to the hornblende. The properties of the clinopyroxene (determined in part on the universal stage) are: $\gamma=1.719$, $\alpha=1.689$, $Z\wedge c=48°$, $2V=60°$. Andesine is zoned from $An_{45}$ out to about $An_{35}$.

### *Ferrohastingsite schist*

Amphibole 4 is from a heavy, very dark green lineate schist that consists of ferrohastingsite along with only 2 per cent of sphene, 0.5 per cent of oligoclase or quartz, and 0.5 per cent of epidote. The unusual rock composition listed in Table 3 should be very reliable. In thin section the amphibole is seen to be evenly colored, medium-grained, and moderately prismatic; {100} tends to parallel the schistosity and the prism axes define the rock's strong lineation. The sphene is very fine-grained and is scattered evenly throughout the amphibole as though it had separated from it.

### *Biotite-hornblende tonalite*

Amphibole 5 is from one of the most mafic rocks of the batholith; however, its properties are essentially the same as those of hornblendes from other batholith rocks. The calculated chemical analysis of the tonalite must be considered as approximate only because many point counts showed the rock to be heterogeneous, especially with respect to the ratio of biotite to hornblende and of quartz to plagioclase. The approximate mode is:

| | | | |
|---|---|---|---|
| quartz | 14.0 | magnetite | 1.0 |
| plagioclase ($An_{34}$) | 58.0 | epidote | 0.2 |
| hornblende | 14.5 | apatite | 0.1 |
| biotite | 12.0 | zircon | tr. |

Plagioclase is subhedral to euhedral and is zoned in an oscillatory manner from cores of about $An_{46}$ to rims of about $An_{22}$ (as determined by the Rittmann method on the universal stage). Quartz is in fine-grained aggregates between the plagioclase grains, while clots of mafic grains tend to wrap around plagioclase. Hornblende prisms are subhedral and about 1–2 mm. long, and biotite forms ragged anhedra that are twice that size. Hornblende is not rimmed by biotite, though it is locally replaced by it. Coarse-grained pistachite occurs here and there with chloritized biotite. The minor chlorite and fine-grained alteration products of plagioclase are included in the mode as the minerals they replaced.

## PARAGENESIS

The sequence of metamorphic assemblages in basaltic rocks of the Bidwell Bar area is outlined in Fig. 1. The arrows indicate only the principal sources of materials for each mineral of a new assemblage; actually, almost all of the minerals in adjacent columns are linked in some degree.

The derivation of greenschist minerals from basaltic rocks is based purely on textural evidence because igneous relics are very scarce. These

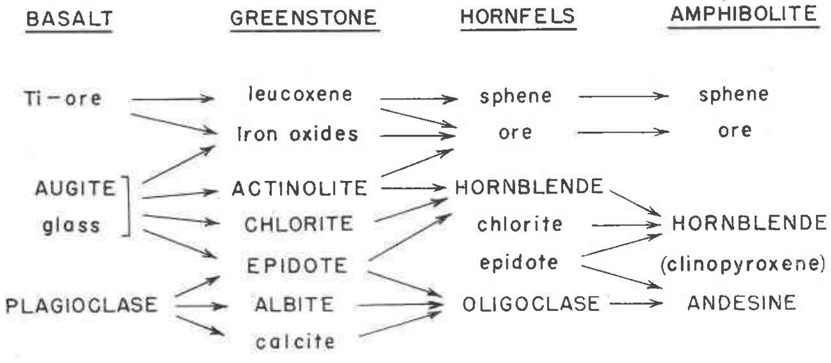

FIG. 1. Sequence of mineral assemblages in metabasaltic rocks of the Bidwell Bar region. The principal minerals are in capital letters.

reactions were definitely earlier than the contact metamorphism, and all of the rocks of the aureole were once similar to the rocks now found in the regional terrane. The conditions of greenschist metamorphism are not critical here, and have already been described (Compton, 1955, p. 17–18).

The progressive contact metamorphic assemblages are essentially isochemical, except that water was lost at each stage. The changes of leucoxene and hydrated iron oxides to ore and sphene, and the conversion of actinolite to hornblende apparently took place abruptly in the outer zone of the aureole. The amphibole reactions involved both the addition of Al to actinolite and the combination of chlorite and epidote to yield more hornblende, with magnetite and water as additional products. The principal partial reactions are:

1) chlorite+epidote+Si→hornblende+Al+Fe‴+water
2) actinolite+Al→hornblende+Si+(Mg, Fe″)
3) Fe‴+Fe″→magnetite

The overall reaction formed by combining these partial reactions is:

actinolite+chlorite+epidote→hornblende+magnetite+water+Mg

For partial reaction 2, the analyses indicate that Mg rather than Fe″ is the dominant product, and it is therefore necessary to consider plagioclase as a reactant with the excess Mg, forming more (though minor) hornblende. In the inner zone of the aureole, aluminous hornblende was increased only slightly by the further reactions of epidote and minor chlorite. In the case of the plagioclase reactions, however, albite reacted with epidote to produce oligoclase in the outer part of the aureole and then continued to react in a progressive way so that plagioclase compositions tend to be more and more calcic as the batholith is approached. The appearance of clinopyroxene near the batholith contact probably involves the destruction of some hornblende; however, there is insufficient data on the compositions and distribution of these pyroxenes to determine whether they were formed by local high temperatures, by the dehydrating effects of the adjacent magma, or simply by local concentrations of Ca and Mg.

The paragenesis of the ferrohastingsite schist involves rocks with unusual compositions. Ferrohastingsite occurs at several localities in the inner zone of the aureole, in one place with abundant andesine and accessory magnetite and sphene, in another place with abundant labradorite, clinopyroxene, and titaniferous ore. In an important exposure on the Cascade road 1,300 feet northeast of the Feather Falls village Forest Service station, ferrohastingsite schist is associated with metacherts, suggesting that the schists were once iron-rich basic tuffs, perhaps palagonite tuffs enriched in iron hydroxides. That they were not impure limy beds that have undergone iron metasomatism is indicated by the fact that they are not associated with tactites that occur in the same part of the aureole. In any case, the hastingsitic amphibole formed because of the high Fe/Mg ratio of the rocks and their low silica content; it cannot be correlated with a higher grade of metamorphism.

The hornblende of the tonalite is notably less aluminous than the hornblendes of the aureole, and this fact, coupled with its large grain size and euhedral (110) faces, indicate that it crystallized from a magma, rather than being xenocrystic after amphibolite. The low alumina content is doubtless a result of partition of materials with aluminous biotite that was growing at the same time.

## Significance of the Actinolite-Hornblende Reaction

Conversion of actinolite and other greenschist minerals to aluminous hornblende is petrologically significant at Bidwell Bar because the two minerals are abruptly superimposed, the rocks involved are extensive, and the reaction produced a textural change that affords a basis for mapping the extent of a new metamorphic environment. How does this abrupt change correlate with what might be expected from the progressive metamorphism of actinolites to hornblendes? Comparison of analyses of many actinolites, hornblendes, and hastingsites (from rocks of various compositions) indicates that these minerals form a continuous solid solution series, with the number of Al atoms in Z positions ranging from 0 to somewhat more than 2 (see esp. Hallimond, 1943, p. 80–87). In metamorphic rocks containing appreciable alumina, the number of Al atoms in Z positions of hornblendes is greater in higher grade rocks than in lower grade rocks, and it seems most reasonable to expect a continuous increment of Al atoms in Z positions of actinolites and hornblendes during the progressive metamorphism of basaltic rocks (Foslie, 1945, p. 98; Turner, 1948, p. 90, 98; Turner and Verhoogen, 1951, p. 465). The inconsistency between these views and the Bidwell Bar paragenesis requires a review of the mineral data that substantiate ideal gradation from actinolite to hornblende in metabasalts. When this is done, it will be possible to consider why the Bidwell Bar metamorphism produced a different paragenesis.

Compositions of all chemically analyzed actinolites and hornblendes from greenschists, greenstones, and epidote amphibolites are presented in Table 4, in order of increasing amount of Al in Z positions. Number 4 was calculated from an unpublished chemical analysis generously furnished by Prof. C. O. Hutton, and the complete analysis and optical measurements, all made by Hutton, are given in Table 5. All of the rocks concerned have compositions reasonably close to that of basalt, although

TABLE 4. NUMBERS OF PRINCIPAL ATOMS IN FORMULAE OF AMPHIBOLES FROM GREENSCHISTS, GREENSTONES, AND EPIDOTE AMPHIBOLITES

| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (Z) | Si | 7.73 | 7.74 | 7.66 | 7.64 | 7.61 | 7.54 | 7.47 | 7.16 | 7.06 | 6.72 | 6.58 | 6.48 |
| | Al | 0.24 | 0.26 | 0.34 | 0.36 | 0.39 | 0.46 | 0.53 | 0.84 | 0.94 | 1.28 | 1.42 | 1.52 |
| (Y) | Al | 0.00 | 0.19 | 0.43 | 0.27 | 0.02 | 0.21 | 0.13 | 0.56 | 0.55 | 0.48 | 0.16 | 0.41 |
| | Ti | 0.02 | 0.03 | 0.04 | 0.04 | 0.05 | 0.08 | 0.04 | 0.14 | 0.08 | 0.06 | 0.05 | 0.07 |
| | Fe''' | 0.00 | 0.12 | 0.09 | 0.25 | 0.28 | 0.42 | 0.52 | 0.33 | 0.32 | 0.57 | 0.64 | 0.59 |
| (X) | Mg | 3.78 | 3.25 | 3.25 | 3.48 | 2.85 | 2.47 | 3.12 | 1.58 | 1.98 | 2.23 | 2.80 | 2.28 |
| | Fe'' | 1.14 | 1.39 | 1.16 | 0.97 | 1.87 | 1.82 | 1.28 | 2.22 | 2.14 | 1.80 | 1.17 | 1.56 |
| | Mn | 0.02 | 0.00 | 0.03 | 0.02 | 0.03 | 0.04 | 0.00 | 0.03 | 0.03 | 0.07 | 0.03 | 0.05 |
| (W) | Ca | 1.93 | 1.90 | 1.92 | 1.68 | 1.73 | 1.60 | 1.57 | 1.68 | 1.63 | 1.69 | 1.99 | 1.92 |
| | Na | 0.39 | 0.15 | 0.24 | 0.27 | 0.27 | 0.44 | 0.41 | 0.39 | 0.19 | 0.28 | 0.18 | 0.35 |
| | K | 0.00 | 0.02 | 0.11 | 0.02 | 0.09 | 0.02 | 0.00 | 0.15 | 0.26 | 0.07 | 0.08 | 0.10 |
| | OH | 2.14 | 1.94 | 1.56 | 2.00 | 2.02 | 1.92 | 2.06 | 2.06 | 2.02 | 1.89 | 2.60 | 2.14 |

1. "Hornblende from fibrous hornblende-clinozoisite-albite schist, Limebury point, Salcombe Estuary' South Devon." (Tilley, 1938, p. 505).
2. "Hornblende from hornblende-epidote-albite schist below Signal Station, Prawle Point, Start District, South Devon." (Tilley, 1938, p. 504).
3. Actinolite from mafic greenstone. (Tables 1 and 2, analysis 1).
4. Actinolite from albite-epidote-chlorite-actinolite schist of Chl. 3 subzone; 32 chains E.N.E. of Jessie Peak, Mid-Wakatipu Survey District, Western Otago, New Zealand. Analyst, C. O. Hutton.
5. "Hornblende out of chlorite-epidote-albite-amphibolite (26); 0.4 mile south-east of Loch Gair Hotel, Argyll." (Wiseman, 1934, p. 368).
6. "Actinolite from albite-stilpnomelane-actinolite-schist, No. 2646, 56 chains east of Billy Goat Creek-Arrow River junction, western Otago." (Hutton, 1940, p. 13–14).
7. "Amphibole from albite-epidote-actinolite-calcite-schist, No. 2718, from the summit of Coronet Peak, Wakatipu region." (Hutton, 1938, p. 209; 1940, p. 13).
8. "Hornblende out of garnet-biotite-epidote-albite-amphibolite (68/4), 0.2 mile N. 51° E. from northern end of Loch-na-Craige, near Achahoish, South Knapdale." (Wiseman, 1934, p. 382).
9. "Hornblende out of biotite-epidote-albite-amphibolite (65/4)." Same locality as 8. (Wiseman, 1934, p. 383).
10. Hornblende from hornfelsic metadiabase. (Tables 1 and 2, analysis 2).
11. Hornblende from hornblende schist (with quartz, oligoclase, epidote, and biotite); northwest of Lake Pappilanselka, Orivesi. (Seitsaari, 1953, p. 89, table 5).
12. Hornblende from stratified hornblende schist (with quartz, oligoclase, epidote and biotite); northeast of Lake Vaavujarvi, Orivesi, Finland. (Seitsaari, 1953, p. 89, table 4).

some were originally clastic rocks. Numbers 1 and 2 are from the greenschists of the Start region of Devonshire, England; numbers 4, 6, and 7 are from the widespread greenschists of the Otago region, New Zealand; numbers 5, 8, and 9 are from the progressively metamorphosed epidiorites (metadiabases) of the Central and Southwest Highlands of Scotland; numbers 11 and 12 are from epidote-oligoclase amphibolites (originally basic sediments) of the Tampere schist belt, Finland; and numbers 3 and 10 are from greenstone and epidote-oligoclase-hornblende hornfels of the Bidwell Bar area. It is notable that the actinolites from the lower grade parts of the various areas are closely comparable (numbers 1, 2, 3, 4, and 5). None, however, are pure "end member" actinolite; apparently

TABLE 5. COMPOSITION AND PHYSICAL PROPERTIES OF ACTINOLITE FROM OTAGO, NEW ZEALAND

| | | |
|---|---|---|
| $SiO_2$ | 54.07 | $\alpha = 1.629$ |
| $Al_2O_3$ | 3.81 | $\beta = 1.643$ |
| $TiO_2$ | 0.40 | $\gamma = 1.650$ |
| $Fe_2O_3$ | 2.45 | $\gamma - x = 0.021$ |
| $Cr_2O_3$ | 0.08 | $Z \wedge c = 19°$ |
| NiO | 0.03 | $2V_\alpha = 73° \pm 2°$ |
| MgO | 16.45 | X = colorless |
| FeO | 8.25 | Y = pale green |
| MnO | 0.24 | Z = pale green with bluish tinge |
| CaO | 11.13 | $Z \geqq Y > X$ |
| $Na_2O$ | 1.03 | $G_{20°} = 3.17$ |
| $K_2O$ | 0.17 | |
| $H_2O^+$ | 2.13 | Analysis and physical measurements by C. O. Hutton. See Table 4 for locality description. |
| $H_2O^-$ | 0.11 | |
| Total | 100.35 | |

even at lowest metamorphic grade a quarter or third of an atom of the 8 Z atoms is Al, a fact that must be kept in mind when comparing actinolites of metabasaltic rocks with those of less aluminous metamorphic rocks. The actinolites of the Otago region are of particular interest because they show a variation within the greenschist realm itself. The validity of progressive metamorphism in these rocks is undeniable, being based on regional mapping of zones of progressive mineral and textural changes, keyed by several thousand thin sections (Hutton and Turner, 1936). The chlorite zone was divided into four subzones on the basis of degree of reconstitution of the original graywacke beds. In Chl. 3 subzone, from which amphibole number 4 was collected, the rocks are fine-grained schists with a few relics of sedimentary grains, while in Chl. 4 subzone, the source of amphiboles 6 and 7, the rocks are exceptionally coarse-grained and even show segregation banding. In keeping with this progressive change, actinolites 6 and 7 have more Al in Z positions than does actinolite 4, and they are also more aluminous than any analyzed actinolites from greenschists. Still another amphibole from Chl. 4 subzone, not listed in Table 4 because it is from too mafic a rock, has 0.71 atom of Al in the 8 Z positions (Hutton, 1940, p. 15; 1956, p. 231–232). The approach of these amphiboles to aluminous hornblende may be explained by Turner's view (1948, p. 39) that "In Chlorite 4 the temperature appears to have been somewhat higher than in the other subzones, and was certainly maintained for a much longer period." Certainly, the compositional range of these amphiboles supports the concept of gradual conversion of actinolite to hornblende during progressive metamorphism.

The amphiboles studied by Wiseman (5, 8, and 9 of Table 4) supply an additional step in the progressive increase of Al in Z positions during increasing grade of metamorphism. Proof of progressive metamorphism lies in the zonal pattern of mineral changes, based in this case on the classical mineral zones mapped in metashales of the Southern Highlands (Barrow, 1912, p. 274–279; Tilley, 1925). The compositional change from the greenschist actinolite (number 5) to the two hornblendes from epidote amphibolites of the garnet zone (numbers 8 and 9) is distinct; however, the garnet zone amphiboles are not much more aluminous than Hutton's Chl. 4 subzone amphiboles, and they are less aluminous than the hornblendes of typical epidote-free amphibolites of comparable areas. Therefore, these garnet zone hornblendes fit exactly into a serial change from greenschist through epidote amphibolite to amphibolite facies conditions, further supporting the view that reactions of actinolite to hornblende are continuous, not discontinuous.

Just as surely as in the Southern Highlands, the epidote amphibolites at Bidwell Bar represent an intermediate step in the conversion of greenschists to epidote-free amphibolites. Furthermore, the texture of the hornfels from which amphibole 10 (Table 4) was separated indicates it was a massive metadiabase, directly comparable with Wiseman's epidiorites; nor was it any more aluminous than the rocks from which Wiseman separated his two hornblendes. The one obvious difference between the Bidwell Bar rocks and those of either the Southern Highlands or the Otago region is that contact metamorphism produced the rocks at Bidwell Bar while regional metamorphism produced the other two assemblages. What are the physical differences between these particular cases of contact and regional metamorphism that account reasonably for the differences in mineral parageneses? Probably, there are three principal factors that produced the differences, and perhaps the most important of these was the difference between rate of escape of water and rate of increase of temperature during inception and progress of the amphibole reactions described above. The theoretical basis for this factor has been presented in some detail by Thompson (1955) and in part by Yoder (1955, p. 513–516). On this basis, I interpret the gradational amphibole changes in the Otago and Highlands schists as occurring in broad terranes which were heated so slowly that water never accumulated rapidly enough to inhibit the progress of the reaction at each temperature increment. Deformation and continuous recrystallization may have been important factors in moving water continuously out of the terrane. In the Bidwell Bar aureole, rapid increase in temperature relative to rate of escape of water created a high water pressure almost at the outset of metamorphism, and the amphibole reaction was inhibited in the low temperature range. By the time that escape of fluids was sufficient to allow appreciable reaction, temperatures were so high as to produce an aluminous hornblende. It is possible that a complicating abnormality may have been produced by fluids forced through the outer part of the aureole by rapid dehydration nearer the batholith.

Another factor that probably contributed to the contrast in mineral parageneses is the difference between rates of reaction at any one temperature and rates of heating. In the regional terranes, temperatures rose slowly enough so that even sluggish (low temperature) reactions were usually at or near equilibrium. The coarse-grained Otago schists of Chlorite subzone 4 seem to emphasize this factor strongly. In contrast to this true progressive metamorphism, the contact rocks were heated so rapidly that low temperature reaction of actinolite was volumetrically ineffective in the relatively short period of time between inception of heating and rapid reaction at intermediate to high temperature. Finally, the third factor is based on the degree of comminution and mixing of constituents before and during recrystallization. Dynamic metamorphism of the rocks of the Southern Highlands and Otago produced a fine-grained mixture of mineral units that could react readily as temperatures increased. Because of the lack of granulation in the outer zone of the Bidwell Bar aureole, only the finest grained constituents of the greenschists could react easily in the lower temperature range, a situation substantiated by minor hornblende overgrowths and relict actinolite cores in the larger Bidwell Bar amphiboles.

There is insufficient data to determine which of these factors was dominant in controlling the amphibole parageneses of the two environments; however, epidote amphibolites from other areas indicate the Bidwell Bar conditions were not unique. The epidote amphibolites of the Tampere schist belt of Finland are comparable in several ways to the Bidwell Bar epidote amphibolites, although there is apparently no chance of tracing the progression of changes from greenschists to amphibolites in the Tampere terrane. The hornblendes of these rocks are aluminous (11 and 12 of Table 4) and in several cases they are heterogeneous, like those in the outer part of the Bidwell Bar aureole (Seitsaari, 1953, p. 87–88). With regard to their origin, Seitsaari (1953, p. 96) "suggests that the crystallization of the blue-green hornblende in the Tampere schists is generally related to a late increase of temperature, and that the penetrative movements have been weak, if not terminated, during its formation." A close approach to contact metamorphic conditions is supported by these facts: 1) the hornblende occurs as porphyroblastic prisms that cut across the schistosity, 2) the hornblende occurs only in the finer grained rocks, and 3) the analyzed hornblendes were collected less than a mile from granitic intrusions of batholithic size.

A case of contact metamorphic amphiboles showing abrupt reaction relations is reported from the Misaka series of Japan by Sugi (1931). No analyses of these amphiboles are available, but Sugi studied textural and refractive index changes carefully enough so that there is little doubt but that he detected the same amphibole relations as those at Bidwell Bar. The Misaka rocks are basic to intermediate lavas and greenschists that have been progressively metamorphosed to epidote amphibolites and amphibolites near a quartz diorite intrusion. In the transition between greenschists and amphibolites, actinolite and hornblende occur together with epidote, sodic plagioclase, and chlorite. It is notable that the new blue-green hornblende of this transition forms sharp rims on actinolite, or else clear-cut prisms that lie on or near large actinolite grains (Sugi, 1931, p. 115–116). In mafic schists, hornblende typically has formed first in areas containing chlorite, indicating the importance of this mineral in the formation of aluminous hornblende. Perhaps the greatest value of Sugi's work on these rocks was to demonstrate that abrupt reaction of actinolite to hornblende may be detected without laborious separations and analyses.

Considering the general situation presented above, the actinolite-hornblende reaction must be considered carefully in assigning rocks of basaltic composition to one of the metamorphic facies. Wiseman's epidote amphibolites fit exactly the albite-epidote amphibolite facies of many authors (see esp. Turner, 1948, p. 88–89), but the compositions of Hutton's actinolites from the Chl. 4 subzone indicate that some metabasalts from the biotite zone might well contain hornblende rather than actinolite. According to the picture presented above, the temperature realm of albite-epidote amphibolite facies in the Bidwell Bar region is represented by metastable greenschists and greenstones that lie outside the aureole; in the aureole itself, conditions of the transitional facies have been essentially overstepped, and the aureole is entirely in amphibolite facies. The abrupt appearance of cordierite and andalusite in the outermost parts of some pelitic aureoles may be explained by the same sort of overstepping of transitional assemblages. Before the hornblende analyses of the Bidwell Bar amphiboles were available, I interpreted the oligoclase-epidote-hornblende hornfelses as representing a stress-free variant of the albite-epidote amphibolite facies (Compton, 1955, p. 42). On the basis of the hornblende reaction, however, I would reject this view, much as Thompson questioned the "stress" and "antistress" control of aluminum silicates in regional and contact terranes (Thompson, 1955, p. 98).

The eventual disappearance of epidote from epidote amphibolites provides a useful physical basis for defining the upper limit of the epidote amphibolite facies as used by Foslie (1945), Seitsaari (1953, p. 95), Barth (1952, p. 338), and others. This limit is, of course, well beyond the upper limit of the albite-epidote amphibolite facies. The analyses presented above show clearly that hornblendes occurring with epidote and oligoclase are almost as aluminous as those of epidote-free amphibolites, indicating that the actinolite-hornblende reaction takes place over a lower temperature range than the epidote-plagioclase reaction.

## Conclusions

Through more data are wanting, it is likely that the series actinolite-hornblende-hastingsite is controlled by temperature, and that a continuous reaction series might be produced by ideally progressive metamorphism of basaltic rocks. Discontinuities in the series appear to be valuable in pointing up physical conditions of metamorphism, especially those affecting reaction rates. It is suggested that serial analyses of any temperature-variant solid solution series will be of unique value in interpreting metamorphism of a given suite of rocks, even where the absolute temperature-pressure dimensions of the series are not known.

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