

TWO-AMPHIBOLE ASSEMBLAGES IN THE SYSTEM
ACTINOLITE-HORNBLLENDE-GLAUCOPHANE¹CORNELIS KLEIN, JR., *Department of Geological Sciences,
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ABSTRACT

This study gives electron probe analyses and optical descriptions for twenty-two amphibole pairs, which include, actinolite-hornblende, actinolite-glaucophane, hornblende-glaucophane, hornblende-hornblende, and several pairs which are intermediate in composition between hornblende and glaucophane. One pair is quoted from the literature.

In actinolite-hornblende pairs the hornblende always has the lower $Mg/(Mg+Fe)$ ratio. The one hornblende-hornblende pair shows a similar fractionation. In actinolite-glaucophane pairs glaucophane has lower $Mg/(Mg+Fe)$ as well as lower $Si/(Si+Al)$ ratios. In four out of six hornblende-glaucophane pairs the glaucophane has a smaller $Mg/(Mg+Fe)$ ratio than the hornblende, whereas in two pairs this is reversed. The $Si/(Si+Al)$ fractionation between these two highly aluminous phases is very irregular. Four pairs, which consist of glaucophane and hornblende-glaucophane compositions, have $Mg/(Mg+Fe)$ and $Si/(Si+Al)$ fractionation patterns very different from those observed in the other pairs.

In a few of the 2-amphibole assemblages homogeneous, separate grains of the two amphiboles coexist in random intergrowth, but the majority of textures show complex zonation and patches of the two amphiboles in composite grains. The contact between the two amphiboles has been found to be optically and chemically sharp in every 2-amphibole assemblage, except one. These 2-amphibole assemblages are evidence for the probable existence of miscibility gaps in the system actinolite-hornblende-glaucophane at relatively low temperatures. The majority of the rocks in which these assemblages occur are part of the greenschist or epidote amphibolite facies, and the glaucophane schist facies, all of which were formed at relatively low temperatures.

INTRODUCTION

Many studies have dealt with the extent of various chemical substitutions in the clin amphiboles of tremolite-actinolite [$Ca_2(Mg,Fe)_5Si_8O_{22}(OH,F)_2$], hornblende [$(Na,Ca)_{2-3}(Mg,Fe^{2+})_4(Al,Fe^{3+})Si_6Al_2O_{22}(OH,F)_2$] and glaucophane-riebeckite [$Na_2Mg_3Al_2(Si_6O_{22})(OH,F)_2$ to $Na_2Fe_3^{2+}Fe_2^{3+}(Si_8O_{22})(OH,F)_2$] compositions. Some of these studies are based upon collections of large numbers of chemical analyses for green, blue-green and blue clin amphiboles (Kunitz, 1930, Hallimond, 1943, and Sundius, 1946), and other studies are based upon the occurrence and analysis of two or more optically distinct Na-Ca clin amphiboles in one assemblage (for references, see Table 1).

In his study of the hornblende "family" Kunitz (1930) presents analyses for several amphiboles that are intermediate in composition between tremolite-actinolite and glaucophane. Similar examples of two "riebeckite-tremolite" compositions are given in Klein (1966). Such

¹ Mineralogical Contribution No. 459, Harvard University.

TABLE 1. LITERATURE REPORTS OF COEXISTING AMPHIBOLES IN THE RANGE OF ACTINOLITE-HORNBLLENDE-SODIUM AMPHIBOLE COMPOSITIONS

Coexisting actinolite and hornblende	
Reference, rock type and location	Description
<i>Compton (1958)</i> . Mafic greenstone (albite-actinolite-hornblende-epidote-chlorite-leucocene-calcite), Bidwell Bar region, Calif.	Actinolite abruptly overgrown by green hornblende. Sharp boundary between the two amphiboles. Electron probe analyses are given in Table 2 (2-3). Compton's paper gives complete analyses for two amphiboles that were not in physical contact.
<i>Dunham (pers. comm.)</i> . Quartz diorite (quartz-microcline-plagioclase-biotite-hornblende-actinolite), Blodgett Forest Pluton, El Dorado County, Calif.	Colorless actinolite and green hornblende coexist in single amphibole grains. The margins between the 2 amphiboles are often irregular but sharp. Chemical analyses given in Table 2 (2-4).
<i>Miyashiro (1958)</i> . Actinolite-epidote-chlorite-plagioclase, sometimes with minor amounts of quartz, calcite and biotite (Zone "B"). Gosaisyo-Takanuki district, Abukuma Plateau, Japan.	Blue-green hornblende occurs as rims around actinolite crystals, sometimes as patches within actinolite crystals and sometimes as independent crystals. In all cases the boundary between the 2 amphiboles is sharp. Checks for sharpness were made with tilted sections on the universal stage.
<i>Seitsaari (1956)</i> . "Plagioclase porphyrite" consisting of plagioclase (An5-6), biotite, hornblende, actinolite and epidote. Tampere schist belt, Finland.	Blue-green hornblende with almost colorless or faintly greenish kernels. The two different parts of the amphibole crystals are homoaxial. Seitsaari gives complete analyses for the dark and lighter colored amphibole fractions.
<i>Shido and Miyashiro (1959)</i> . Schists similar to those given above under Miyashiro, and epidiorites (hornblende-chlorite-epidote-oligoclase schist) from Aberfeldy, Perthshire, Scotland.	Hornblende occurs in parallel growth with, as patches within, and also as rims around the actinolite. The boundary between the two amphiboles is always sharp. Sharpness of the contact was checked in several samples with tilted thin sections. Electron probe analyses of one such occurrence are given in Table 2 (2-2).
<i>Wiseman (1934)</i> . "Abnormal epidiorite" (a unratized gabbro consisting of labradorite, augite, biotite, and 2 types of amphibole). Southwest Highlands, Scotland.	Describes hornblende of variable color in an epidiorite; sometimes it shows a light green kernel with a blue-green rim. The description suggests actinolite and hornblende compositions.
Coexisting hornblende (or actinolite) and Na-amphibole, and zoned Na-amphiboles	
<i>Banno (1958)</i> . Glaucophane schists, Omi district, Niigata, Japan.	Colorless actinolite and blue-green glaucophane parts in single crystals. Usually the cores of the crystals are actinolite, the rims glaucophane. However, the reverse is also observed.
<i>Bloxam (1960)</i> . Crossite amphibolite composed of hornblende, crossite, epidote, albite, sphene, apatite and garnet. Girvan-Ballantrae Complex, South Ayrshire, Scotland.	Hornblende mantled by crossite rims. Complete hornblende and crossite analyses are given by Bloxam. The Ca-content of the crossite is probably high because of epidote and green hornblende contamination (Bloxam, personal communication).
<i>Borg (1956)</i> . Glaucophane schists near Healdsburg, Calif.	Hornblende in cores of glaucophane crystals. Borg interprets these occurrences as glaucophane replacement of hornblende.
<i>Dudley (1967)</i> . Glaucophane schists, Tiburon Peninsula, Marin County, Calif.	Coexisting actinolite and glaucophane; as zones in single crystals and as separate crystals.

TABLE 1. (Continued)

Reference, rock type and location	Description
<i>Ernst, et. al. (pers. comm.)</i> , Glaucophane schists from Tiburon Peninsula and Goat Mountain, Calif. and the Shirataki district, Shikoku, Japan.	Actinolite and glaucophane coexist in parts of single crystals, and as separate crystals. Electron probe analyses are given for six such pairs, and conventional analyses for one other pair.
<i>Iwao (1939)</i> . Monzonite and dolerite. Nayosi district, Sakhalin, Japan.	Zoned crystals with hastingsite cores and arfvedsonite rims with a transitional layer between them. Barkevikite crystals rimmed by brown-green hornblende. The contact between the hornblende and the barkevikite appears to be sharp.
<i>Iwasaki (1960a)</i> . Magnesioriebeckite-barroisite-Mg-rich glaucophane-garnet-muscovite-piedmontite-aegirine-albite-quartz schists. Eastern Shikoku, Japan.	Three layer zoning in amphiboles: a nearly colorless core (Mg-rich glaucophane), colored mantle (magnesioriebeckite) and a rim of green amphibole. A complete chemical analysis is given for the magnesioriebeckite.
<i>Iwasaki (1960b)</i> . "Quartz schists" similar to those described above. Eastern Shikoku, Japan.	Barroisite rims around glaucophane cores (barroisite is similar in composition to hornblende with a large Na component, Deer <i>et al.</i> , 1963). Also description of magnesioriebeckite cores with barroisite rims.
<i>Iwasaki (1963)</i> . Glaucophane schists and magnesioriebeckite-Mn-garnet-piedmontite-stilpnomelane-quartz schists. Kôtu-Bizan area, eastern Shikoku, Japan.	Gives examples of many types of zonation: actinolite (core)-glaucophane (rim); glaucophane (core)-actinolite (rim); glaucophane (core)- barroisite (rim); magnesioriebeckite (core)- barroisite (rim); magnesioriebeckite (core)- actinolite (rim); barroisite (core)- glaucophane (rim); barroisite (core)- magnesioriebeckite (rim). In all cases the boundaries between the 2 amphiboles were found to be sharp. Electron probe analyses of similar occurrences are given in Tables 4 (4-3) and 5 (5-2, 5-3).
<i>Lee et al. (1966)</i> , Glaucophane schists, Cazadero area, Sonoma County, Calif.	Actinolite and glaucophane are present as distinct individual grains, but more often a single amphibole grain may consist of both actinolite and glaucophane. Complete conventional analyses for the 2 amphiboles are given.
<i>Miyashiro and Iwasaki (1957)</i> , Garnet-aegirine-amphibole-muscovite-quartz schist with minor hematite and apatite. Bizan, Shikoku, Japan.	Detailed description of zoned magnesioriebeckite of which the core is colorless, the rim blue and pleochroic. The boundary between the rim and core is said to be sharp. A complete analysis is given for the blue rim material (magnesioriebeckite) and the core is stated to be a magnesioriebeckite with less Fe, on the basis of optical properties.
<i>Van der Plas and Hügi (1961)</i> . Metamorphic ophiolite consisting of epidote, magnetite and blue-green amphibole, cut by an albite vein. Vals, Switzerland.	A ferrian sodium-amphibole with dark blue cores and light blue rims. Electron probe analyses are given in Table 5 (5-5).
<i>Yagi (1953)</i> . Monzonite and syenite. Morutu district, Sakhalin, Japan.	Hastingsite rimmed by arfvedsonite. The transition zone between the two amphiboles appears to be gradational.

intermediate compositions show that under certain geological conditions a continuous chemical series exists between actinolite and riebeckite-glaucophane. Under different geologic conditions, however, a chemical

discontinuity, or miscibility gap, may exist between tremolite-actinolite and sodium amphiboles. Sundius (1947), in his study of the solid solution relations in the amphibole group shows that, on the basis of the chemistry of a large number of Na- and Na-Ca-amphiboles, a "zone of unmixing exists between the alkaline and lime-alkaline hornblendes, though the unmixing area may be restricted" (p. 35). He furthermore shows, also on the basis of many analyses, that if there is a chemical discontinuity between actinolite and hornblende compositions, such "an area of unmixing cannot be very great" (p. 33). Hallimond (1943, p. 74) suggests, on the basis of a collection of 196 hornblende analyses, that there may be a break in composition between the tremolite-actinolite series which grades into "common hornblende" and pargasitic hornblende with a notable content of alkalis [Idealized pargasite composition: $\text{NaCa}_2\text{Mg}_4(\text{Al}, \text{Fe}^{3+})\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH}, \text{F})_2$; Deer *et al.*, 1963].

Many authors have described coexistences of two or more clin amphiboles whose compositions are within the actinolite-hornblende-sodium amphibole group. Table 1 gives some of the references and short descriptions of such occurrences. The most frequently described texture is that of zonation of one amphibole by the other. Several authors, however, also describe occurrences of separate, individual crystals of both coexisting amphiboles. The majority of the amphibole identifications in Table 1 are based upon optical study and only very few chemical analyses are available for the two members of the described pairs. Compton (1958) gives complete analyses for a hornblende and an actinolite, however, the analyzed samples were obtained from specimens in which the two amphiboles were not in direct contact. Bloxam (1960) gives complete analyses for coexisting hornblende and crossite. The crossite analysis may be too high in CaO because of epidote and hornblende impurity in the analysis separate (Bloxam, pers. comm.). Seit-saari (1956) gives analyses for the light and dark colored fractions of an actinolite-hornblende association. These analyses were probably not made on highly purified separates because of the difficulty in separating the hornblende rims from the actinolitic cores. Lee *et al.* (1966) give complete conventional analyses for coexisting actinolite and glaucophane, and W. G. Ernst, Y. Seki, H. Onuki and M. C. Gilbert (pers. comm.) give electron probe analyses for six occurrences of actinolite and glaucophane, and conventional analyses for an additional actinolite-glaucophane pair.

It is the purpose of this study to provide further quantitative chemical evidence for the existence of compositional discontinuities between actinolite, hornblende and sodium amphiboles, under certain geologic conditions.

CHEMICAL ANALYSES

Chemical analyses were made after detailed optical study had revealed the presence of two optically distinct amphiboles. A few samples which showed different pleochroism in different parts of grains, were subsequently proven to be homogeneous in composition through electron probe analysis of the various differently colored areas. In these instances differences in optical orientations, rather than changes in composition were the cause for the difference in pleochroic colors.

Analyses of twenty-one two-amphibole pairs were made with an electron microprobe (Applied Research Laboratories—EMX) on carbon-coated thin sections. The analyses of one additional pair (assemblage 2-1) were made on handpicked grains mounted in a carbon-coated polished section. The conditions of analysis were similar to those described in detail in Klein (1968). The instrumental conditions and reference standards were the same, except for the calibration curve for Na_2O . The Na_2O curve given in Klein (1968) ranges from 0 to 5 weight percent Na_2O . For this study, in which glaucophane-type amphiboles were analyzed, the calibration curve needed to be extended to higher Na_2O values. Unable to locate homogeneous analyzed sodium amphiboles, I used two homogeneous, analyzed aegirines for the high Na_2O range of the standard curve. The analyses for these aegirines (no. 17A—10.37 weight percent Na_2O and no. 15B—6.19 weight percent Na_2O) are given in Klein (1966). Because of the very close similarity in matrix between these clinopyroxenes and the sodium amphiboles, the pyroxene Na_2O values could indeed be used for the extension of the sodium amphibole calibration curve. A TiO_2 calibration curve was based upon one analyzed gedrite with 0.29 weight percent TiO_2 , and two analyzed hornblendes containing 0.38 and 1.90 weight percent TiO_2 respectively.

The majority of the amphiboles in this study were analyzed for nine elements. As the ARL electron probe allows simultaneous analysis of a maximum of three elements, the samples had to be introduced and relocated in the electron probe a minimum of three times. In order to facilitate location and relocation in the instrument, the analysis area on each of the thin sections was marked and this same area was photographed on a bench microscope at 30 \times and 300 \times magnification. As it is very difficult, even with the marking of the analysis areas and the accompanying photographs of the area, to locate the electron beam accurately by means of the optical system only, the X-ray intensity of Ca-K α or in some cases Fe-K α was monitored throughout the analysis procedure by means of a recorder or audioamplifier read-out. The combination of optical observation of the amphibole grains in thin section with the graphical or audio read-out of the Ca-K α or Fe-K α X-ray intensity made it possible to locate and relocate accurately the chemically and optically distinct parts of a single amphibole grain or of a two-amphibole assemblage made up of separate grains. Ca-K α or Fe-K α radiation was selected for continual monitoring because the Ca or Fe contents, or both, are greatly different in the coexisting amphiboles in this study. The continual monitoring of the Ca-K α or Fe-K α X-ray output also prevented the analysis of erroneous intermediate compositions which are the result of the geometry of the intergrowth of two phases rather than of their true chemical composition.

The maximum relative error in the weight percent values for SiO_2 , FeO, CaO and MnO is estimated to be approximately ± 2 –3 percent of the amount present. The maximum relative error in the Na_2O , K_2O , Al_2O_3 , MgO and TiO_2 values is probably about ± 5 percent. The anhydrous totals for the electron probe analyses in Tables 2, 3, 4 and 5 range from 95.3 to 99.7 weight percent, with the majority of the totals between 96.5 and 98.0 weight percent. These totals provide an approximate indication of the completeness of the analyses, but they cannot be used for an estimate of the H_2O content of the amphiboles because Fe_{total} has been recalculated as FeO only. As the Fe_2O_3 component is unknown in these analyses and as this component is a very major one in the sodium amphiboles, it

has been impossible to recalculate the weight percent figures on the basis of 23 oxygens or on the basis of a fixed number of cations (e.g. 15). Furthermore, because of the absence of Fe_2O_3 values, it is impossible to make nomenclature distinctions in the sodium amphiboles and in the hornblendes which are dependent upon a knowledge of the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio. All sodium amphiboles in this study have a high Al_2O_3 content which ranges from about 6 to 12 weight percent and all of these are referred to as glaucophane. It is possible, however, that some of these would turn out to be crossite or ferroglaucophane if the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio were known. Similarly no detailed nomenclature distinctions were made in the hornblende or actinolite analyses. All predominantly Ca-rich and Al-rich amphiboles are referred to as hornblende, whereas amphiboles with a high Ca-content and a relatively low Al_2O_3 content (less than 4.8 weight percent) are referred to as actinolite.

COEXISTING ACTINOLITE AND HORNBLLENDE COMPOSITIONS

Table 2 gives the electron probe analyses for seven pairs of coexisting actinolite and hornblende. The analyses are arranged in order of decreasing $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of the actinolite. Four of these 2-amphibole rocks are metadolerites or metabasalts described by Compton (1955 and 1958) from the Bidwell Bar region, California. Another such assemblage (no. 2-2) was described by Shido and Miyashiro (1959) from the epidiorites in Scotland. Assemblage no. 2-1 is from an amphibolite in Madagascar described by Lacroix (1939) and no. 2-4 is part of a quartz-diorite in Eldorado County, California, described by A. C. Dunham (pers. comm.). Detailed assemblage descriptions, locations and references are given at the bottom of Table 2.

The four 2-amphibole occurrences of the Bidwell Bar region are very similar in texture. The hornblende occurs as irregular patches within, and as irregular zones around coarse grained, euhedral to subhedral actinolite grains. The hornblende is highly pleochroic from colorless to dark green whereas the actinolite is almost colorless with a faint green tinge. In some grains actinolite is the most abundant phase whereas in others hornblende makes up the greater part. The hornblende-actinolite interface is always sharp optically; electron beam scanning across such interfaces with the electron probe has confirmed this sharpness.

The two amphiboles in the epidiorite (assemblage 2-2) show textures very similar to those described above. Large, subhedral hornblende crystals show colorless actinolite zones and patches which are randomly distributed throughout the host crystals. The contacts between the two amphiboles are optically sharp.

The textural relationships of the two amphiboles in the quartz-diorite (assemblage 2-4) are practically identical with those of the epidiorite occurrence. Again large, subhedral crystals show irregular zones and patches of hornblende in actinolite, and vice versa.

The two amphiboles in the amphibolite from Tsintbolovolo, Madagascar (assemblage 2-1) are texturally very different from the occurrences

TABLE 2. COEXISTING ACTINOLITE AND HORNBLLENDE COMPOSITIONS

	2-1 Ac	2-1 H	2-2 Ac	2-2 H	2-3 Ac	2-3 H	2-4 Ac	2-4 H	2-5 Ac	2-5 H	2-6 Ac	2-6 H	2-7 Ac	2-7 H
SiO ₂	55.0	48.9	57.2	51.2	55.5	49.5	54.7	46.3	53.4	47.1	52.2	45.7	51.3	44.8
TiO ₂	n.d. ^a	n.d.	0.1	0.0	0.0	1.2	0.2	1.1	0.3	0.3	0.3	0.7	0.0	0.3
Al ₂ O ₃	3.2	9.6	1.8	8.0	3.5	4.9	3.1	7.8	3.7	9.5	3.5	9.1	4.8	11.2
FeO	9.4	10.7	8.8	10.2	9.4	17.7	11.4	16.6	12.9	17.4	16.1	18.6	16.5	21.8
MnO	0.2	0.2	0.2	0.2	0.3	0.6	0.5	0.5	0.6	0.4	0.6	0.7	0.4	0.5
MgO	20.0	16.8	18.6	16.1	16.9	10.8	14.5	11.5	16.0	13.9	14.9	11.2	13.4	8.0
CaO	9.7	11.2	11.2	10.8	12.5	10.2	12.8	11.4	10.8	9.9	11.2	10.4	11.1	10.7
Na ₂ O	0.5	1.7	0.2	0.9	0.2	0.8	0.2	1.0	0.4	1.1	0.5	1.0	0.3	1.2
K ₂ O	n.d.	n.d.	0.0	0.2	0.1	0.4	0.0	1.0	0.0	0.1	0.0	0.2	0.2	0.3
	98.0	99.1	98.1	97.6	98.4	96.1	97.4	97.2	98.1	99.7	99.3	97.6	98.0	98.8
100 Mg/(Mg+Fe)	79.2	73.8	79.1	73.9	76.3	52.1	69.4	55.2	68.9	58.7	62.2	51.8	59.2	39.5
100 Ca/(Ca+Na)	91.5	78.3	97.1	87.3	97.4	87.4	97.4	86.4	94.1	83.8	92.6	85.2	96.1	83.3
100 Si/(Si+Al)	93.6	81.2	96.5	84.5	93.1	89.5	93.8	83.5	92.5	80.8	92.7	81.0	90.1	77.4

^a n.d.—not determined.

assemblage 2-1: Actinolite-hornblende amphibolite. The green hornblende shows very pronounced and frequent exsolution of a colorless phase (probably actinolite) parallel to 101 and 100 of the hornblende. Location: Tsintobovolo, Madagascar. Originally reported by Lacroix (1939), no. 111-1. (Number 9779 of the Museum National d'Histoire Naturelle, Paris).

assemblage 2-2: Epidiorite consisting of hornblende-actinolite-chlorite-epidote-oligoclase (24-28% An). Location: west-north-west of Craze, Aberfeldy, Perthshire, Scotland. Described in Shido and Miyashiro (1959). Obtained from S. O. Agrell (no. 14736).

assemblage 2-3: mafic greenstone consisting of actinolite-hornblende-epidote-albite-chlorite-leucosene and calcite. Location: Bidwell Bar region, California. Described in detail by Compton (1958). Compton's no. BR-1-16. Compton gives complete analyses of the actinolite and also of a hornblende that is found close to, but not touching the actinolite.

assemblage 2-4: Quartz-diorite consisting of quartz-microcline-plagioclase-biotite-hornblende-actinolite. Location: Bldgett Forest Pluton, El Dorado County, Calif. Dunham's no. 64. (p. 8, comm.).

assemblage 2-5: Semschistose metadiorite consisting mainly of actinolite with hornblende rims and spots, plagioclase (relict labradorite and metamorphic oligoclase), epidote and chlorite, with minor quartz and pyrite. Location: Roadcut on north side of Orville-Forestwood road, Bidwell Bar quadrangle, 1800 ft. east and 1250 ft. south of the NW corner section 15, T 19 N, R 4 E. Ref: Compton (1955). Compton's no. BR-5-71.

assemblage 2-6: Massive metadiorite consisting mainly of actinolite with hornblende rims and spots, plagioclase (about An₆₀) and olivine, chlorite, muscovite or ilmenite or both, and minor pyrite. Location: east of low ridge 1 mi. NW of Lake Wyandotte, Bidwell Bar quadrangle, 2000 ft. east of road 2300 ft. north of the SE corner of section 8, T 19 N, R 5 E. Ref: Compton (1955). Compton's no. BR-6-51.

assemblage 2-7: Massive metadiorite consisting mainly of plagioclase (about An₆₀), intermixed with zoned actinolite and deeply colored hornblende, epidote, magnetite and/or both biotite and minor quartz. Location: Cut on Feather Fall R.R., Bidwell Bar quadrangle, 1500 ft. west and 200 ft. south of NE corner of section 32, T 20 N, R 5 E. Ref: Compton (1955). Compton's no. BR-C-8.

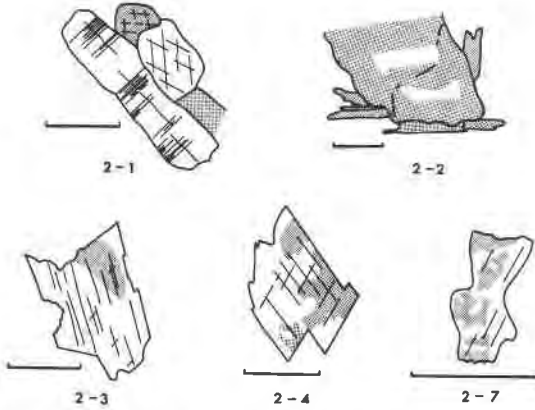


FIG. 1. Sketches of actinolite-hornblende relationships. The actinolite is unshaded, the hornblende is shaded. The numbers refer to the assemblages in Table 2. The bar length represents 0.5 mm. In assemblage 2-1 separate crystals of actinolite and hornblende coexist. Both phases show abundant exsolution lamellae parallel to $10\bar{1}$ (shown in the actinolite grain) and some parallel to 100. The thickness of the exsolved lamellae is considerably less than one micron. Illustrations of the other assemblages show a variety of 2-amphibole textures within single grains. In each of the cases shown the contact between the two amphiboles is optically sharp at high magnification ($600\times$).

described above. The hornblende and actinolite in this rock do not occur in zonal or patchy intergrowths but as separate, individual crystals that coexist side by side. The major part of the rock is made up of green, somewhat pleochroic hornblende and the remainder is composed of very light green, to almost colorless and non-pleochroic actinolite. The rock is equigranular and the grains of the two amphiboles are very closely interwoven. It was possible, in this case, to handpick individual colorless and dark green grains from the handspecimen for electron probe analysis. The green hornblende shows abundant exsolution lamellae parallel to $(10\bar{1})$ and (100) . These lamellae are so small in scale, with a maximum thickness of approximately $1/4$ micron, that their chemical composition could not be determined with the microprobe. It is very likely that these lamellae have an actinolite composition, similar to that of the coexisting, equigranular and colorless actinolite. Similar occurrences have been described in coexisting equigranular hornblende and cummingtonite in which the hornblende shows exsolution lamellae of cummingtonite (Jaffe *et al.*, 1968; Klein, 1968 and Ross *et al.*, 1968).

Illustrations of the above textures are given in Figure 1. Figure 2 shows the tieline distributions for the two-amphibole assemblages in Table 2, in terms of three molecular ratios, $100 \text{ Mg}/(\text{Mg} + \text{Fe})$, $100 \text{ Si}/(\text{Si} + \text{Al})$ and $100 \text{ Ca}/(\text{Ca} + \text{Na})$. The chemically and crystallographically

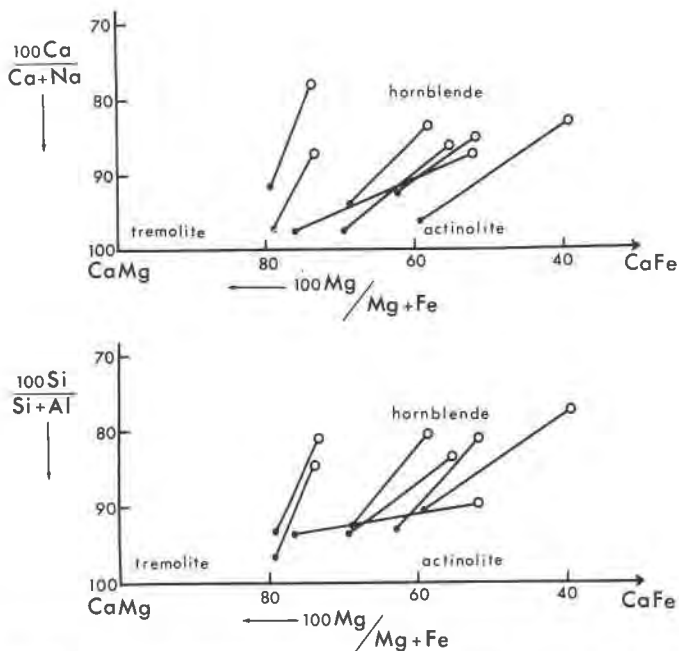


FIG. 2. Major element fractionation between coexisting actinolite and hornblende compositions. Because of the high Al content of the hornblendes, their total composition is only partially represented in the upper diagram. The hornblende points may be considered as projections onto the CaMg-CaFe-NaMg-NaFe plane from another component, Al_2O_3 . The lower diagram, along the $100 \text{ Si}/(\text{Si}+\text{Al})$ axis, shows how far these hornblendes lie off the CaMg-CaFe-NaMg-NaFe plane. Actinolites are represented by solid black dots, hornblendes by open circles.

more significant ratios, $100 \text{ Mg}/(\text{Mg}+\text{Fe}^{2+})$ and $100 \text{ Si}/(\text{Si}+\text{Al}^{\text{IV}})$ could not be computed because the electron probe method does not allow the determination of the Fe^{3+} content. The major element fractionation is similar in each of the seven pairs; the more aluminous phase (hornblende) is also the more iron rich. The hornblende contains also an appreciable Na_2O content, whereas the maximum in the coexisting actinolite is 0.5 weight percent Na_2O .

COEXISTING ACTINOLITE AND GLAUCOPHANE COMPOSITIONS

The analyses of five actinolite-glaucophane pairs are given in Table 3, in order of increasing Fe content of the actinolite. The calcium-rich amphiboles are referred to as actinolite because of their low Na_2O and Al_2O_3 contents, the maxima being 1.7 and 3.6 weight percent respectively. The first four analysis pairs are new electron probe analyses,

TABLE 3. COEXISTING ACTINOLITE AND GLAUCOPHANE COMPOSITIONS

	3-1 Ac	3-1 G	3-2 Ac	3-2 G	3-3 Ac	3-3 G	3-4 Ac	3-4 G	3-5 Ac	3-5 G
SiO ₂	55.8	56.6	54.8	54.8	53.6	55.8	54.0	54.6	54.04	55.04
TiO ₂	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.11	0.22
Al ₂ O ₃	3.3	12.2	2.1	10.4	3.6	12.6	2.7	7.2	2.85	9.06
FeO	7.2	6.6	9.7	15.9	11.2	11.6	11.3	14.5	11.79	11.62
MnO	0.2	0.1	0.1	0.1	0.0	0.0	0.3	0.2	—	—
MgO	18.7	13.2	18.3	8.0	17.2	10.6	16.9	10.9	14.62	9.64
CaO	10.3	0.9	10.1	0.4	10.1	0.8	9.4	1.7	10.36	3.58
Na ₂ O	1.1	7.7	1.4	7.2	1.2	7.8	1.7	6.4	1.52	5.50
K ₂ O	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.09	0.05
	96.7	97.3	96.6	96.8	97.0	99.2	96.4	95.5	2.10 (Fe ₂ O ₃)	2.83 (Fe ₂ O ₃)
									2.02 (H ₂ O+)	1.99 (H ₂ O+)
100 Mg/(Mg+Fe)	82.2	78.2	77.0	47.2	73.3	61.9	72.7	57.3	99.50	99.53
100 Ca/(Ca+Na)	84.3	6.1	80.4	2.9	82.6	5.3	75.6	12.7	65.3	54.6
100 Si/(Si+Al)	93.5	79.8	95.8	81.7	92.7	79.0	94.5	86.6	79.0	26.6
									94.3	83.9

assemblage 3-1: Epidote-actinolite-glaucophane schist with poikiloblastic lawsonite and accessory sphene, chlorite and white mica; some epidote with clinzoisite cores. Location: Tiburon Peninsula, Marin County, Calif. (loose block, Lat. 37° 54' 25" N, Long. 122° 29' 25" W). Ref: Dudley (1967). Dudley's no. 677-307.

assemblage 3-2: Epidote-garnet-actinolite-glaucophane rock with sodic pyroxene, chlorite, white mica, sphene, rutile, apatite and pumpellyite. Location: Tiburon Peninsula, Marin County, Calif. (loose block, Lat. 37° 54' 45" N, Long. 122° 29' 05" W). Ref: Dudley (1967). Dudley's no. 677-761.

assemblage 3-3: Garnet-omphacite-actinolite-glaucophane schist with accessory quartz, white mica, rutile, sphene, apatite and zircon. Location: Shubin District, Southern Urals, U.S.S.R. Obtained from P. F. Dudley; no. 677-D. Ref: Chesnokov (1959).

assemblage 3-4: Actinolite-glaucophane-chlorite-muscovite-sphene. Location: Junction School, Healdsburg, Calif. Similar assemblages described in Borg (1956), Borg's number 331-M-H2. Sample obtained from P. F. Dudley.

assemblage 3-5: Glaucophane-actinolite-epidote-muscovite-garnet-chlorite-sphene and traces of apatite, rutile and pumpellyite. Location: Cazadero area, Sonoma County, Calif. (Lee *et al.*, 1966). V. C. Smith analyst. Analyses of the coexisting phases in this schist are given in Lee *et al.* (1966).

whereas the fifth pair is quoted from the literature (Lee *et al.*, 1966).

All five pairs occur in glaucophane schists, four from Californian localities and one (3-3) from the southern Urals, U.S.S.R. Detailed assemblage descriptions, locations and references are given at the bottom of Table 3. The textures of the amphiboles in all five samples are similar. The two amphiboles occur as distinct, individual, subhedral grains which are closely and randomly intergrown, as well as composite grains in which actinolite and glaucophane make up different parts of the same grain. Illustrations of the textures are given in Figure 3. The

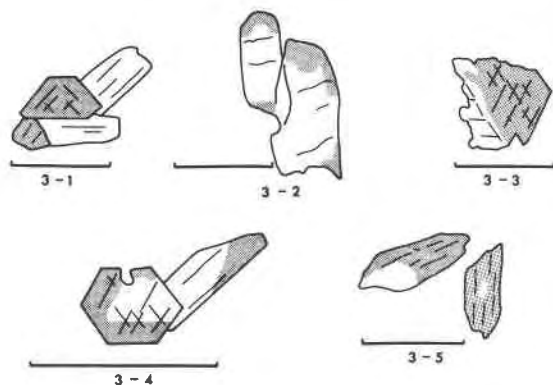


FIG. 3. Sketches of actinolite-glaucophane relationships. The actinolite is unshaded, the glaucophane is shaded. The numbers refer to the assemblages in Table 3. The bar length represents 0.5 mm. In assemblage 3-1 separate crystals of actinolite and glaucophane coexist. The other illustrations show some of the actinolite-glaucophane interrelations within single grains. In all assemblages in Table 3 the contacts between the two amphiboles were found to be optically sharp at high magnification (600 \times). The illustration for assemblage 3-5 was taken from Lee *et al.* (1966).

actinolite is pleochroic from colorless to light or dark green, whereas the glaucophane is generally more strongly pleochroic from colorless, to light blue, to dark purplish blue.

Figure 4 shows the tieline distributions for the two-amphibole assemblages in Table 3, in terms of three molecular ratios. The major element distribution is similar in each of the five pairs. The Mg/(Mg+Fe) ratio is larger in the actinolite than in the coexisting sodium amphibole, and the Al-content is higher in the glaucophane than in the actinolite. The compositional difference (*i.e.* tieline separation) between the two amphiboles of assemblage 3-5 is less than that of the other four pairs. The amphiboles of assemblage 3-5 were separated by heavy liquid techniques (Lee *et al.*, 1966) and it seems very likely that such a separa-

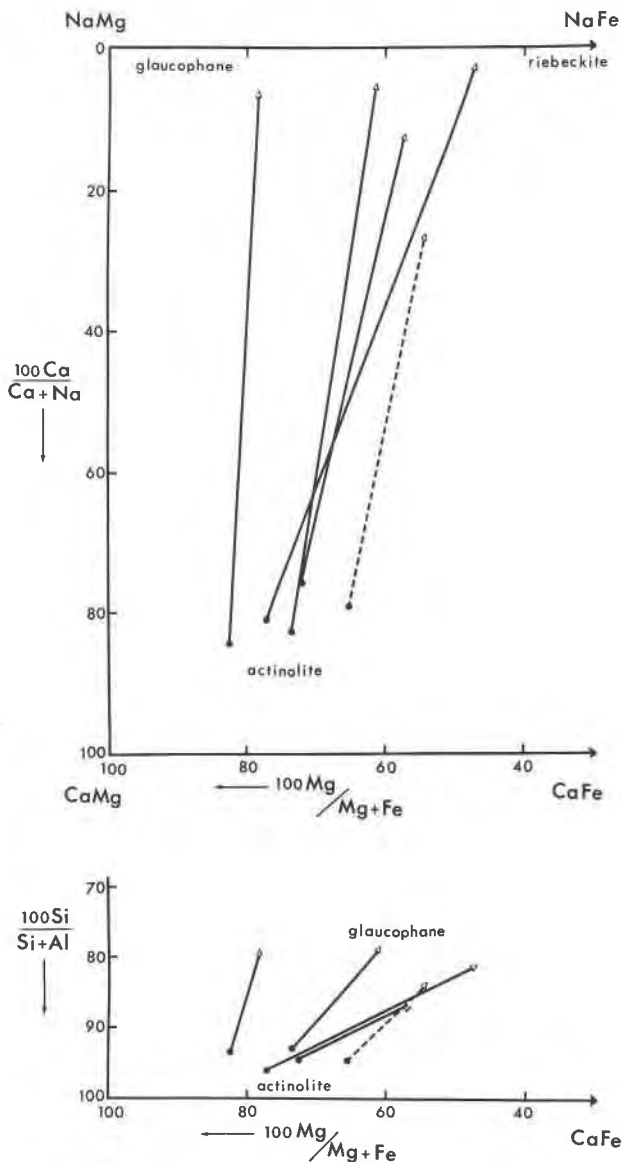


FIG. 4. Major element fractionation between actinolite and coexisting glaucophane compositions. Because of the high Al content of the sodium amphiboles, their total composition is only partially represented in the upper diagram. The glaucophane points may be considered as projections onto the CaMg-CaFe-NaMg-NaFe plane from another component, Al_2O_3 . The lower diagram shows how far the glaucophane, as well as actinolite compositions lie off the CaMg-CaFe-NaMg-NaFe plane, along the $100 Si/(Si+Al)$ axis. Actinolites are represented by solid black dots, glaucophane by open triangles. The tieline for pair 3-5, reported by Lee *et al.* (1966), is dashed.

tion would not produce completely pure analysis separates. A small admixture of one amphibole in the separate of the other would tend to reduce the chemical difference between the two members of the pair.

COEXISTING HORNBLENDE AND GLAUCOPHANE COMPOSITIONS

Table 4 gives the compositions of six hornblende-glaucophane pairs. The analyses are arranged in order of increasing Fe content of the hornblende. The Ca-rich amphiboles are referred to as hornblende because their Al_2O_3 content, which ranges from 4.9 to 14.8 weight percent Al_2O_3 , is considerably higher than that of the actinolites in Table 3. Furthermore, the Na_2O content of these hornblendes is generally larger than that of the actinolites in Table 3, and ranges from 1.3 to 3.6 weight percent Na_2O .

All six pairs are found in glaucophane schists. Assemblages 4-1, 4-2, 4-4, and 4-5 are from California, 4-3 is from Japan, and 4-6 from Scotland. Detailed assemblage descriptions, locations and references are given at the bottom of Table 4.

The textures of these 2-amphibole occurrences are similar to those of the actinolite-glaucophane pairs. In assemblage 4-1 the glaucophane occurs as irregular zones and patches within and around nearly colorless, subhedral hornblende crystals. In assemblage 4-2 the glaucophane is found as patches within, as well as distinct, separate grains between hornblende grains. In this assemblage glaucophane makes up about ten percent of the total amphibole content. In assemblage 4-3 the majority of the amphibole is glaucophane; hornblende makes up about five percent of the total amphibole content. The hornblende is found as distinct zones within and around the edge of glaucophane crystals. Assemblage 4-4 is fine grained and the glaucophane and hornblende occur mainly as separate, closely interwoven, individual crystals. The texture of the amphiboles in assemblage 4-5 is very similar to that of assemblage 4-2. Hornblende is very abundant in this rock and the glaucophane is found at the corners and edges of coarse, subhedral hornblende grains, as well as irregular, small grains interstitial to the larger hornblende crystals. Assemblage 4-6 shows individual hornblende and glaucophane grains which are closely intergrown, as well as zones of glaucophane around and within the subhedral hornblende. In each of the above occurrences the contact between hornblende and glaucophane is optically as well as chemically sharp. The textures of some of the samples are illustrated in Figure 5.

In Figure 6 the tieline distributions are shown for the two-amphibole assemblages in Table 4, in terms of three molecular ratios. In four of the six pairs the glaucophane has a somewhat lower $\text{Mg}/(\text{Mg}+\text{Fe})$

TABLE 4. COEXISTING HORNBLende AND GLAUCOPHANE COMPOSITIONS

	4-1 H	4-1 G	4-2 H	4-2 G	4-3 H	4-3 G	4-4 H	4-4 G	4-5 H	4-5 G	4-6 H	4-6 G
SiO ₂	51.6	55.3	52.2	55.4	53.9	57.4	52.5	55.7	43.5	54.5	46.9	53.8
TiO ₂	0.2	0.0	0.1	0.0	n.d. ^a	n.d.	0.0	0.0	0.7	0.1	0.2	0.0
Al ₂ O ₃	7.6	7.2	5.2	6.7	4.9	10.8	5.9	12.4	14.8	9.1	9.0	6.6
FeO	9.7	14.0	10.5	14.2	10.9	7.6	12.0	11.0	13.0	13.7	18.2	17.7
MnO	0.2	0.2	0.3	0.5	0.7	0.4	0.3	0.1	0.3	0.2	0.4	0.2
MgO	16.0	12.0	16.3	11.4	16.5	14.8	14.5	10.2	12.3	10.1	10.1	10.4
CaO	10.1	0.5	8.9	1.5	7.2	0.8	9.4	0.8	10.1	0.5	9.1	1.7
Na ₂ O	1.3	7.9	2.7	6.8	3.6	7.4	1.7	7.8	2.9	7.4	3.3	6.4
K ₂ O	0.2	0.0	0.2	0.0	n.d.	n.d.	0.1	0.0	0.5	0.1	0.3	0.0
	96.9	97.1	96.4	96.5	97.7	99.2	96.4	98.0	98.1	95.7	97.5	96.8
100 Mg/(Mg+Fe)	74.6	60.5	73.4	58.9	73.0	77.7	68.2	62.2	62.9	56.8	49.7	51.1
100 Ca/(Ca+Na)	81.8	3.0	64.7	10.6	52.5	5.5	75.6	5.3	66.2	3.2	60.4	12.7
100 Si/(Si+Al)	85.3	86.8	89.5	87.6	90.3	82.0	88.4	79.3	71.4	83.6	81.6	87.5

n.d. not determined.

assemblage 4-1: Omphacite-hornblende-glaucophane schist with lawsonite, apatite, rutile and sphene. Location: Tiburon Peninsula, Marin County, Calif. (loose block, Lat. 37° 54' 25", Long. 122° 29' 15"). Ref: Dudley (1967), no. 677-569.

assemblage 4-2: Garnet-glaucophane-hornblende-sphene-rutile-chlorite. Location: Tiburon Peninsula, Marin County, Calif. Ref: Dudley (1967) no. 677-C. Precise location unknown. Sample originally collected by S. Rice and deposited in Berkeley Un. collection.

assemblage 4-3: Glaucophane (colorless)-hornblende (light green)-epidote-muscovite-quartz-apatite-stilpnomelane schist. Location: Bizan, Sikkim, Japan. Similar rock described in Iwasaki (1960a). Obtained from Iwasaki; his no. S311082.

assemblage 4-4: Omphacite-glaucophane-hornblende-lawsonite-chlorite-pumpellyite-muscovite-sphene-pyrite. Location: Ward Creek, Cazadero, Calif. From E. Essene's

collection (no. 665-C-13), described in Essene (1967). Sample obtained from P. F. Dudley.

assemblage 4-5: Garnet-hornblende-glaucophane schist with accessory epidote, omphacite, chlorite, pumpellyite, rutile, sphene and apatite. Location: Tiburon Peninsula, Marin County, Calif. (loose blocks, Lat. 37° 54' 20", Long. 122° 29' 30"). Ref: Dudley (1967), no. 677-433.

assemblage 4-6: Epidote-glaucophane-hornblende-sphene, and lesser albite, apatite, and garnet (described under "crossite-amphibolites", Blossam, 1958, p. 7). Location: Kneekormal, in the Girvan-Ballantrae complex, South Ayrshire, Scotland. Blossam's no. RSS2F. Blossam (1958) gives complete analyses of coexisting crossite and hornblende (p. 9).

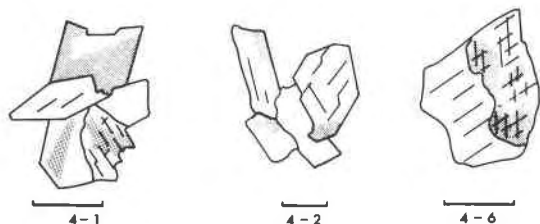
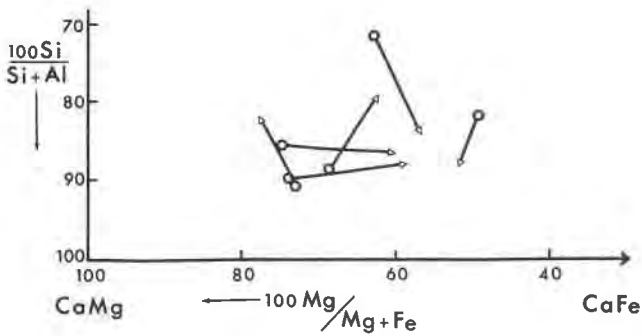
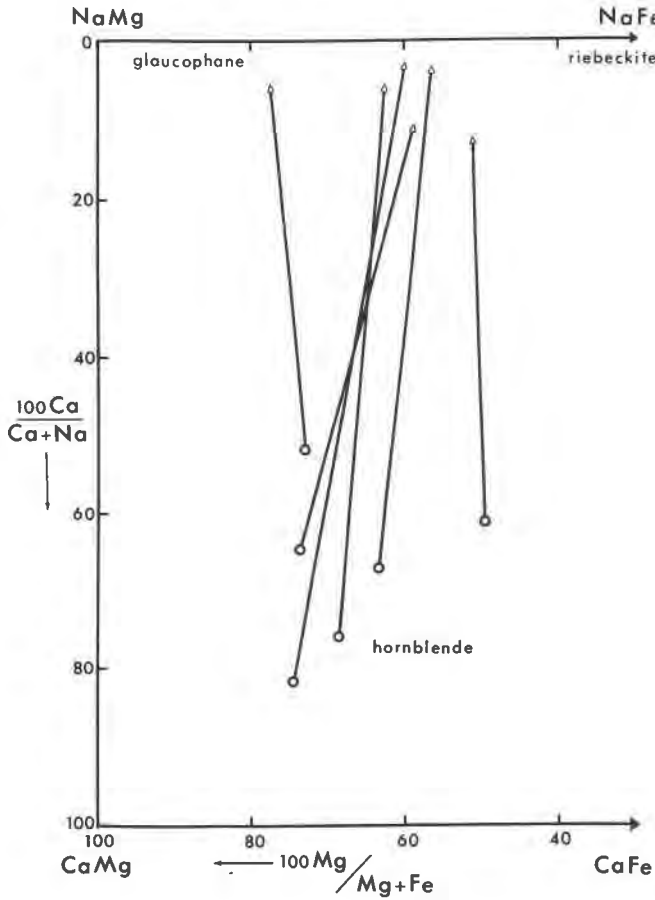


FIG. 5. Sketches of hornblende-glaucophane relationships. The hornblende is unshaded, the glaucophane is shaded. The numbers refer to Table 4. The length of the bar represents 0.2 mm. Although the illustrations show intergrowths of the two amphiboles within single grains only, a few of the assemblages (e.g. 4-6) also contain separate, closely intergrown, crystals of hornblende and glaucophane. The contacts between the two amphiboles were found to be optically sharp in all assemblages of Table 4.

ratio than the coexisting hornblende. In two of the pairs the $Mg/(Mg+Fe)$ ratio of the hornblende is very slightly lower than that of the glaucophane. If the ratio $Mg/(Mg+Fe^{2+})$ could have been evaluated, it would probably be higher in the glaucophane than in the coexisting calcic amphibole, because the Fe^{3+} content is undoubtedly larger in sodium amphiboles than in hornblende. The Al fractionation between the glaucophane and the coexisting hornblende is highly variable, as can be seen in the lower part of Figure 5. In assemblage 4-3 the glaucophane is the more Al-rich phase whereas in assemblage 4-5 the hornblende has the higher Al_2O_3 content. This inconsistent pattern of Al-fractionation between the two highly aluminous phases, hornblende and glaucophane, as expressed by the ratio $100 Si/(Si+Al)$, may be caused by a number of factors, some of which are: (1) The inappropriateness of the ratio $Si/(Si+Al)$. If the ratio $Si/(Si+Al^{IV})$ could have been computed, it might not have shown such inconsistencies. The Al in glaucophane is largely octahedrally coordinated, whereas hornblende probably has both octahedrally and tetrahedrally coordinated Al; (2) A strong temperature dependency for this fractionation (the



FIG. 6. Major element fractionation between coexisting hornblende and glaucophane compositions. Because of the high Al content of both coexisting phases, their total composition is only partially represented in the upper diagram. The hornblende and glaucophane points may be considered as projections from another component, Al_2O_3 , onto the CaMg-CaFe-NaMg-NaFe plane. The lower diagram shows how far these compositions lie off the CaMg-CaFe-NaMg-NaFe plane, along the $100 Si/(Si+Al)$ axis. Hornblendes are represented by open circles, glaucophanes by open triangles.



samples in Table 4, and Figure 5, are collected from different geologic conditions within the glaucophane schists, and it may well be that the Fe/Mg fractionation, which is quite consistent, is not as sensitive to differences in temperature as is the Al-fractionation); (3) The substitution of Fe^{3+} for Al^{3+} , which cannot be evaluated from the electron probe results and (4) The influence of the composition of the other phases in the assemblage.

COMPOSITIONS OF OTHER COEXISTING AMPHIBOLES

Table 5 gives the compositions of five amphibole pairs in which the compositions of the two coexisting amphiboles are such that they cannot be described under the above subdivisions of actinolite-hornblende, actinolite-glaucophane, or hornblende-glaucophane. The two amphibole members in the metadolerite or metabasalt (5-1) are both hornblendes. This assemblage is very similar to the rocks described in Table 2, in which the two coexisting amphiboles are actinolite and hornblende. A dark green colored hornblende (H_2) occurs as irregular patches within, and as irregular zones along the outer edges of coarse grained, euhedral to subhedral, light green hornblende grains (H_1). The contacts between the two hornblendes are optically sharp at high magnification (600 \times). An illustration of this occurrence is given in Figure 7.

In assemblages 5-2, 5-3, 5-4 and 5-5 the compositions of one or both members of the amphibole pair are intermediate between hornblende and sodium amphibole. In Table 5 these compositions are referred to as hornblende-glaucophane (HG). In these intermediate members the ratio $100 \text{ Ca}/(\text{Ca}+\text{Na})$ is close to 50 percent, and ranges from 23.8 to 67.5 percent.

In assemblage 5-2 an almost colorless amphibole with a very slight bluish tinge and weak pleochroism (from colorless to very light greyish blue) makes up about 80 percent of the total amphibole content. This amphibole, referred to as hornblende-glaucophane in Table 5, occurs as euhedral to subhedral grains between and around which a blue glaucophane is found. This highly pleochroic glaucophane (colorless to light blue, to purplish blue) occurs as small individual grains between, as well as distinct relatively narrow zones within, the hornblende-glaucophane grains. The contacts between the two amphiboles are optically and chemically sharp. Both amphiboles appear to be homogeneous and show no exsolution lamellae at high magnification. An illustration of the texture is given in Figure 7.

The texture of the two amphiboles in assemblage 5-3 is very similar to that of 5-2. The amount of glaucophane, however, is much greater than in 5-2 and is about the same as that of the coexisting light greyish

TABLE 5. COMPOSITIONS OF OTHER CA-Na-AMPHIBOLE PAIRS

	5-1 H(1)	5-1 H(2)	5-2 HG	5-2 G	5-3 HG	5-3 G	5-4 HG(1)	5-4 HG(2)	5-5 H	5-5 HG
SiO ₂	47.4	45.4	52.8	54.6	53.5	53.6	49.4	52.2	52.8	49.4
TiO ₂	0.4	0.6	n.d. ^a	n.d.	7.0	0.2	0.1	0.0	n.d.*	n.d.
Al ₂ O ₃	8.2	11.4	8.8	10.3	7.3	7.5	8.2	7.1	5.3	6.7
FeO	13.6	15.7	9.7	15.4	14.0	18.5	18.8	10.3	14.8	19.2
MnO	0.5	0.4	1.2	0.7	0.7	0.6	0.7	1.1	0.3	0.4
MgO	16.0	11.2	15.7	11.5	12.9	9.3	9.5	15.0	13.5	9.2
CaO	11.1	11.2	5.9	1.1	3.0	1.4	6.5	5.6	10.2	7.4
Na ₂ O	0.4	1.2	5.0	5.8	5.3	5.5	4.0	4.3	2.7	3.0
K ₂ O	0.1	0.3	n.d.	n.d.	0.1	0.2	0.2	0.0	n.d.	n.d.
	97.7	97.4	99.1	99.4	96.8	96.8	97.4	95.6	99.6	95.3
100 Mg/(Mg+Fe)	67.7	62.2	74.2	57.1	62.2	47.2	47.4	72.2	61.9	46.1
100 Ca/(Ca+Na)	94.3	84.0	39.5	9.2	23.8	11.3	47.3	41.8	67.5	57.5
100 Si/(Si+Al)	83.1	77.3	83.6	81.8	86.2	85.9	83.7	86.3	89.6	86.3

n.d. not determined.

assemblage 5-1: Propylitic metadiorite or metabasalt, consisting mainly of hornblende (the microcrysts especially, are flattened and subcrispy and from rather to more deeply green color); and/or, epidote, ilmenite, magnetite or both, and minor quartz (location: Cut Feather Falls, R. Bidwell Bar quadrangle; 700 ft. and 2500 ft. north of the NW corner of section 33, T 20 N, R 5 E, Ref. Compton (1955), no. RR-C-17).

assemblage 5-2: Ca-Na-amphibole (HG); light blue tinge/glaucophane (dark blue highly pleochroic) epidote-quartz-muscovite-garnet chloriteschist with trace of tourmaline, rutile and hematite. Location: Bizan, Shikoku, Japan. Obtained from M. Iwasaki; his no. 5603292.

assemblage 5-3: Ca-Na-amphibole (HG); light blue, somewhat pleochroic/glaucophane (blue, strongly pleochroic, garnet-muscovite-quartz schist, with lesser anatite and hematite. Location: Bizan, Shikoku, Japan. Specimen obtained from M. Iwasaki;

his no. 6601211. Miyashiro and Iwasaki (1957) describe a similar assemblage with macroclinechlorite-glaucophane zoning and minor actinolite.

assemblage 5-4: "Graenschist" consisting of quartz-albite-chlorite-Ca amphibole (dark green HG (1))-Na amphibole (almost colorless-HG (2))-stilpnomelane-white mica-pseudomorph-garnet and a trace of sphene. Location: Shirataki district, Shikoku, Japan. Ref: Ernst *et al.* (pers. comm.), Ernst's no. S-86G.

assemblage 5-5: Metamorphic ophiolite consisting of epidote-magnetite-amphibole and cut by an albite vein. Location: northern Adula region, SW of the village of Vals, Kanton Graubunden, Switzerland. The amphibole was described as a "ferran sodium-amphibole" by van der Plas and Hürf (1961). The original chemical analysis was made by Th. Hugi and E. Strycher on a sample that contained dark and light colored zones.

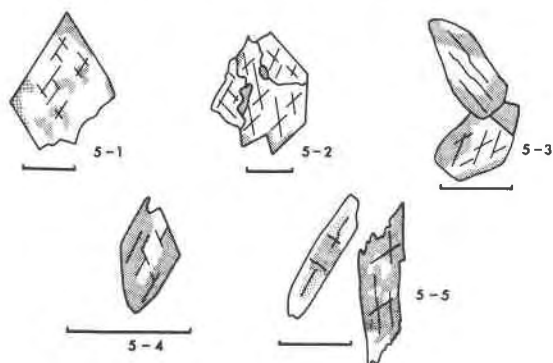


FIG. 7. Sketches of relationship of amphibole pairs whose analyses are given in Table 5. The length of the bar represents 0.2 mm. Assemblage 5-1 consists of two hornblendes, of which one is only very faintly green (H_1) and the other is dark green and highly pleochroic (H_2). H_1 is unshaded in the sketch, and H_2 is shaded. The textural relation of these two hornblendes is very similar to that shown for the actinolite-hornblende (2-4) in Fig. 1. Assemblage 5-2 consists of a Ca-Na-amphibole (HG) with a light blue tinge and a highly pleochroic, blue glaucophane. The Ca-Na amphibole is unshaded in the sketch whereas the glaucophane is shaded. The glaucophane occurs as zones within the other amphibole, as well as separate grains. Assemblage 5-3 is similar to that in 5-2; the Na-Ca amphibole is unshaded in the sketch, the glaucophane shaded. Assemblage 5-4 consists of two amphiboles, both of which have a Ca/Na ratio close to unity. HG_1 is dark green (shaded in the sketch) and HG_2 is practically colorless (colorless in the sketch). The illustration for 5-5 represents two grains of the "ferrian sodium-amphibole", described by van der Plas and Hügi (1961). The left grain shows a gradational change from a dark blue-green (highly pleochroic) center to an almost colorless rim. The right grain shows very irregular, and optically poorly defined zones of colorless amphibole (H) inside predominantly blue-green grains (HG). This occurrence is the only one in this study in which the contact between the two amphibole compositions appears to be gradational.

blue hornblende-glaucophane. Again the contacts between the two amphiboles are optically sharp and no exsolution lamellae were noted in either amphibole. Assemblages 5-2 and 5-3 are from the same area in the glaucophane schists in Japan.

Assemblage 5-4 consists of two amphiboles, both of which have a composition intermediate between hornblende and glaucophane. The ratios $100 \text{ Ca}/(\text{Ca}+\text{Na})$ are very similar in both members, 47.3 and 41.8 respectively. The main difference in composition between the two amphiboles is in their Fe and Mg contents. The dark green, more iron-rich member (HG_1) makes up approximately ninety percent of the total amphibole content of the assemblage. The other member (HG_2) is practically colorless with a slight greenish tinge and occurs as relatively regular zones as well as irregular patches within the subhedral grains of the dark green member. The grain size of this schist is very fine which

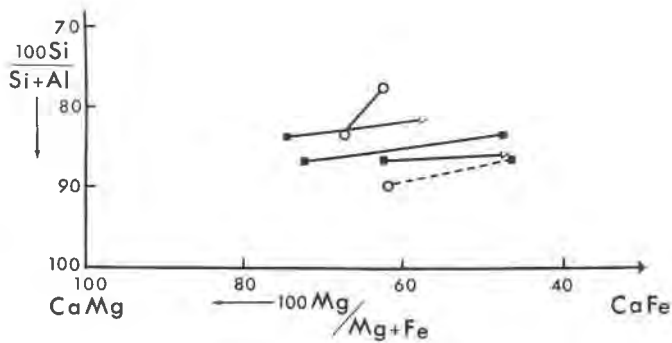
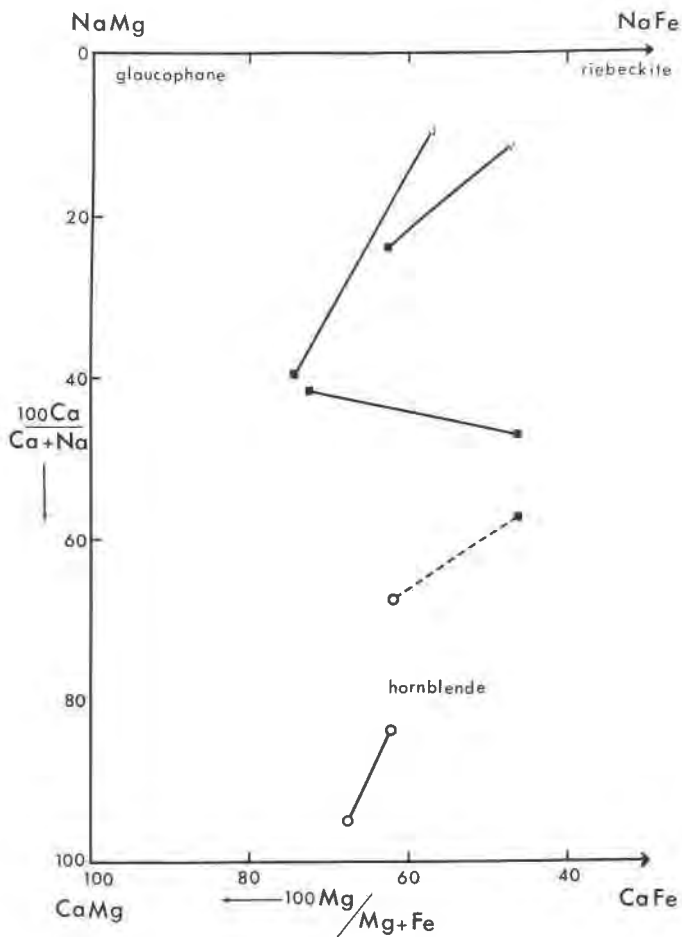
makes it difficult to establish the sharpness of the contact between the two members, at high magnification. It does seem, however, that in this occurrence as in all others described above, the contact is optically sharp. An illustration of the texture is given in Figure 7.

The two amphibole analyses for assemblage 5-5 represent the chemical compositions of the almost colorless zones (H) and the very dark green parts (HG) of the "ferrian-sodium amphibole" described by van der Plas and Hügi (1961). This highly zoned amphibole shows some crystals which are almost continually zoned from a dark blue-green core to a practically colorless rim, with complete color gradation in between. In other crystals the dark green areas occur as irregular patches which alternate with practically colorless patches and zones. In such grains the zones between the two extremes in color appear to be gradational rather than sharp. In many instances these crystals appear mottled with optically poorly defined boundaries between the green and the practically colorless areas. The textures of two grains in assemblage 5-5 are illustrated in Figure 7.

The tieline distributions for the amphibole pairs in Table 5 are shown in Figure 8. The fractionation patterns of the two hornblendes (5-1) are very similar to those of the actinolite-hornblende pairs (Fig. 2). The Fe/Mg and Ca/Na fractionation in the other four 2-amphibole occurrences is very different from any of the previously described occurrences. In samples 5-2 and 5-3 the glaucophane member is more iron-rich, which was also observed in earlier analyses, but the Ca/Na fractionation is considerably less than in the amphibole pairs of Tables 3 and 4. In samples 5-4 and 5-5 the Ca/Na fractionation is very small, almost negligible, and the main difference between the two amphibole compositions is in their Fe and Mg contents.

CONCLUSIONS

The chemical data presented above provide quantitative information on the chemical discontinuities among several members of the Ca-Na amphibole group. The contact between the two coexisting amphiboles is sharp, optically and chemically, in all assemblages except 5-5. In a considerable number of the assemblages (2-1, 3-1, 3-2, 3-3, 3-4, 3-5, 4-2, 4-4, 4-5, 4-6, 5-2) individual, separate grains of the two amphiboles are found in a random, closely interwoven intergrowth (many of these same assemblages also show zonation of one amphibole by or within the other). The texture of these rocks with separate and compositionally different grains is very similar to the textures in closely intergrown assemblages of anthophyllite-hornblende and cummingtonite-hornblende (Klein, 1968). In such occurrences it is very likely that the two members



of the pair represent an equilibrium pair and that the two amphibole compositions represent points across a miscibility gap. In assemblage 2-1 (actinolite-hornblende) and in several of the actinolite-glaucophane assemblages in Table 3 I would conclude, on the basis of the texture of interlocking, homogeneous grains of two different amphiboles, that here also one is dealing with miscibility gaps between actinolite and hornblende, and actinolite and glaucophane. The textures of the amphiboles with zones and patches of the other amphibole, as in Figs. 5 and 7, are much more difficult to interpret. These zoned and patchy textures are highly complex and do not provide clear evidence for replacement of one amphibole by the other. The contacts between the amphiboles in such textures are sharp, but the contact surfaces are highly irregular in form, and in many cases numerous and distinct patches of one amphibole are enclosed in a single grain of the other (see Figs. 1, 3, 5 and 7).

As stated above, assemblages 2-1 and 3-1 represent strong evidence for simultaneous crystallization of two different amphiboles; the chemistry of these two amphibole assemblages are very similar to the chemistries of the other pairs in Tables 2, 3 and 4 and of the first three pairs in Table 5. These similarities in chemistry make me conclude that in all cases in this study, except assemblage 5-5, the two amphibole compositions represent points across a compositional gap. If indeed the complex zones and patches in the composite grains are of replacement origin, the sharp contact between the two compositionally different amphiboles provides evidence for a sharp break in composition between the two amphiboles and this break would be expected if there were a miscibility gap in the system. In other words, replacement would be gradational only if there is a complete compositional range between two members of the system, and it would show abrupt discontinuities if there is a miscibility gap in the system.

The majority of the rocks in Table 2, as well as assemblage 5-1 (Table 5) are metadolerites or metabasalts from the Bidwell Bar area, California. Compton (1955, p. 42) concludes that the metamorphic grade of these rocks lies between that of the greenschist and the amphibolite facies and he suggests that "the temperature of their environment



Fig. 8. Major element fractionation among two coexisting hornblendes (5-1) and between four other Na-Ca and Ca-Na amphiboles. The coordinates are the same as in Fig. 6. Hornblendes are represented by open circles, glaucophanes by open triangles, and intermediate Na-Ca amphiboles by black squares. The tieline for the two compositions in 5-5 is dashed because there appears to be a gradational variation in composition between the two end points.

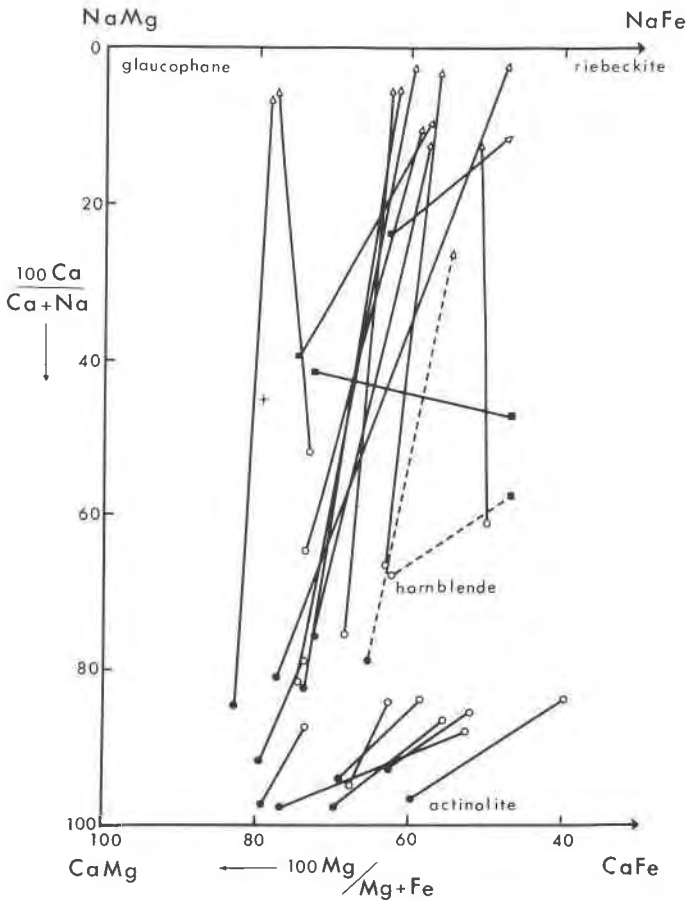


FIG. 9. Composite diagram for the element fractionation of all amphibole pairs in this study. The cross (+) represents the 100 Mg/(Mg+Fe) and 100 Ca/(Ca+Na) ratios for riebeckite-tremolite no. 15 (Klein, 1966) which is a homogeneous amphibole, showing no exsolution lamellae or intergrowths optically or in single crystal X-ray studies. Actinolites are represented by solid black dots, hornblendes by open circles, glaucophanes by open triangles and intermediate Ca-Na amphiboles by solid squares. The tielines for the compositions in assemblages 3-5 and 5-5 are dashed.

is the same as that required by Eskola's epidote-amphibolite facies". These rocks, therefore, represent relatively low temperatures of formation and as such provide the proper temperature conditions for the existence of a possible miscibility gap. That such a gap does indeed exist between actinolite and hornblende, under such conditions, has been shown above. Miyashiro (1958, p. 249) similarly concludes that

"actinolite coexists with blue-green hornblende probably in stable equilibrium owing to a miscibility gap between them", in a relatively low-grade, low pressure, metamorphic terrane. In the higher grade part of the same terrane he states that "this gap vanishes".

A very large number of the assemblages in Tables 3, 4 and 5 are from glaucophane schists in California and Japan for which the general regional environmental conditions lie somewhere between 200° to 400°C, and between 6 to 9 kilobars pressure (Coleman, 1967; Ernst, 1965; Ernst and Seki, 1967). The low temperature of formation of these rocks is the most important factor in the production of possible chemical discontinuities between the amphiboles, and indeed such discontinuities exist, as shown above. In Figure 9, which is a composite diagram of the earlier four figures, the composition of a riebeckite-tremolite (Klein, 1966) is plotted from a metamorphic terrane that has been subjected to considerably higher temperatures than those of the glaucophane schists. This riebeckite-tremolite is a homogeneous phase intermediate in composition between tremolite and riebeckite, and is one of the few available analyses in this compositional area which prove that the miscibility gap, as outlined by many of the pairs in Fig. 9, narrows or possibly closes at somewhat higher temperatures.

The chemistry of assemblages 5-4 and 5-5 are considerably different from the other assemblages in Tables 4 and 5. There is no textural indication, however, that the amphibole pair in assemblage 5-4 does not represent two compositional end points across a possible miscibility gap. Sample 5-5, however, can probably not be interpreted as such. The zonal relations are extremely irregular, sometimes tend to follow cracks in the crystals and are at times gradational in nature. The edges of the amphibole crystals, furthermore, have very irregular and complex contacts with the other phases in the assemblage, and give the impression of having been corroded. This assemblage is the only one which provides evidence for complete compositional gradation between the two end compositions, and may well represent a higher temperature of formation than the other 2-amphibole pairs.

ACKNOWLEDGMENTS

This study is based upon samples collected and studied by geologists the world over, and were it not for their generosity to part with their samples, this work would have been impossible. I am especially grateful to Dr. Priscilla P. Dudley, Boston College and Professor Robert R. Compton, Stanford University, for their cooperation and enthusiasm in providing me with a large number of samples. I wish to express my gratitude to—in alphabetical order—Drs. S. O. Agrell, T. W. Bloxam, A. C. Dunham, W. G. Ernst, B. Evans, M. Iwasaki, O. Mellis, J. OrceI, and L. van der Plas, not only for their generosity but also for their aid in locating a number of samples described in the literature.

I am grateful to W. G. Ernst and J. B. Thompson, Jr. for their helpful discussions, and to W. G. Ernst for his critical reading of the manuscript and his suggestions for its improvement. This work was supported in part by National Science Foundation grant no. GA-1085.

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Manuscript received, April 4, 1968; accepted for publication, August 1, 1968.