LETTER

A five-amphibole assemblage from blueschists in northern Vermont

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Introduction

Multiple amphibole assemblages have been identified in a variety of metamorphic rocks. Recent studies have shown that three- and four-amphibole assemblages commonly contain anthophyllite, gedrite, hornblende, actinolite, and cummingtonite in various combinations (e.g., Robinson and Jaffe, 1969; Robinson et al., 1969; Stout, 1971; Spear, 1980, 1982; reviewed by Robinson et al., 1982). Although it has been suggested on the basis of amphibole crystal chemistry that assemblages containing five amphiboles might occur (e.g., Robinson et al., 1982), no such occurrences have been reported. In the course of a transmission and analytical electron-microscope (TEM–AEM) study of exsolution microstructures in coexisting amphiboles from New England blueschists, we have now identified a five-amphibole assemblage consisting of glaucophane, cummingtonite, winchite, actinolite, and hornblende existing in a single composite grain. This amphibole assemblage differs from those mentioned above in that it contains no orthoamphiboles and contains representative compositions from each of the four major amphibole subgroups of Leake (1978). The purpose of this note is to describe the mode of occurrence and composition for each of the five amphiboles.

Sample description

The samples of blueschist were collected from the Tillotson Peak area in north-central Vermont, near Tillotson Pond (see Fig. 4 in Bothner and Laird, 1987, for locality). Detailed electron-microprobe studies of these rocks have revealed that glaucophane, actinolite, and barroisite coexist in a myriad of complex zoning and intergrowth relationships (Laird and Albee, 1981a). Laird and Albee (1981b) used changing mineral compositions to infer at least three periods of metamorphic mineral growth in these rocks.

The five-amphibole assemblage described here is part of a single composite grain approximately 0.80 mm × 0.15 mm. The composite grain consists of a glaucophane core that is rimmed by several calcic amphibole grains. The glaucophane core also contains an inclusion of calcic amphibole that was most likely linked to the rim amphiboles. Figure 1 is an optical micrograph of the ion-milled TEM sample showing this texture and the locations of the five different amphiboles.

Amphibole compositions and textures

The AEM analyses were collected with a Philips EM420 equipped with an EDAX SiLi X-ray detector and a Princeton Gamma Tech System 4 analyzer. The raw data were reduced following Livi and Veblen (1987). Average amphibole compositions are presented in Table 1. All amphibole formulae were recalculated on a 23-oxygen basis assuming all Fe to be present as FeO.

Cummingtonite

The ferromagnesian amphibole cummingtonite has not been found as discrete grains in these blueschists. However, TEM examination of several samples has shown that cummingtonite commonly occurs as exsolution lamellae in the glaucophane. The lamellae are quite narrow, reaching a maximum width of only about 500 Å (Fig. 2), and are coherently intergrown with the glaucophane. Selected-area electron diffraction (SAED) combined with conventional and high-resolution (HRTEM) imaging techniques show the lamellae to have an unusual crystallographic orientation, being nearly parallel to the $(28\bar{1})$ and $(28\bar{1})$ planes of the host. This orientation for cummingtonite lamellae in glaucophane (from a nearby eclogite) was first reported by Smelik and Veblen (1988).

The average composition of the cummingtonite is shown in Table 1. Compared to the cummingtonite lamellae described by Smelik and Veblen (1988), and most cummingtonite lamellae reported in the literature (e.g., Robinson et al., 1982), these lamellae are significantly enriched in Ca. The supersaturation of the cummingtonite lamellae with respect to Ca has led to the subsequent exsolution of narrow, periodic actinolite lamellae parallel to (100) (Fig. 2b). The Al and Na contents of the cummingtonite may represent analytical contributions from the surrounding glaucophane, as opposed to a significant glaucophane component in solid solution.

Winchite

Like cummingtonite, winchite occurs only as submicroscopic, coherent exsolution lamellae in glaucophane in these rocks. In this sample, the exsolved area containing winchite lamellae (area 2 in Fig. 1) occurs about 100 μm away from the cummingtonite area (area 1 in Fig. 1). Unlike the cummingtonite lamellae, the winchite lamellae are not planar but have curved or wavy interfaces with
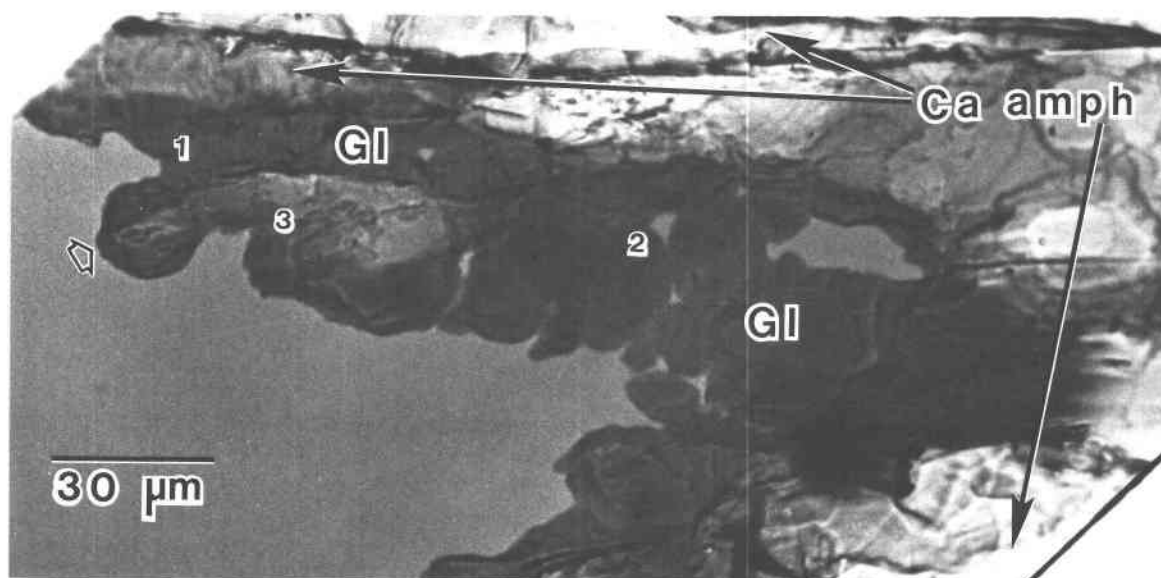
Fig. 1. Cross-polarized light photomicrograph (with ¼-wavelength plate inserted) of composite amphibole grain after final ion-milling. Glaucophane core is surrounded by calcic amphibole grains. Areas are as follows: (1) Abundant cummingtonite lamellae in a glaucophane host (see Fig. 2). (2) Winchite lamellae in a glaucophane host (see Fig. 3). (3) Inclusion of intergrown calcic amphiboles in the glaucophane that was connected to the rim grains before sample preparation. The hollow arrow indicates a region of intergrown actinolite and hornblende (see Fig. 4).

the host (Fig. 3) and therefore have variable orientation with respect to the glaucophane. SAED patterns of the area shown in Figure 3 indicate that the unit cells of the glaucophane and the winchite are nearly identical, consistent with the variable orientation of the lamellae.

The average winchite composition shown in Table 1 is

from lamellae in several grains from the same thin section. This sodic-calcic amphibole is significantly enriched in Si and depleted in Al and Ca compared to the barroisites described by Laird and Albee (1981a) and Laird and Bothner (1986). The barroisite described by these authors occurs as cores in complex composite grains (see

TABLE 1. Average amphibole compositions from AEM for five-amphibole assemblage from Tillotson Pond area, northern Vermont

| | | Glaucophane | | | Cumming- | | | |
		Unexsolved	Cum. host	Win. host	tonite	Winchite	Actinolite	Hornblende
Tetrahedral	Si	7.908	7.934	7.891	7.906	7.629	7.542	6.938
	Al	0.092	0.057	0.109	0.094	0.371	0.458	1.062
Total	T site	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Octahedral	Al	1.592	1.452	1.613	0.149	1.162	0.465	0.713
M1, M2, M3	Ti	0.003	0.001	0.007	0.006	0.001	0.004	0.007
	Mg	2.132	2.252	2.201	3.732	2.733	2.949	2.380
	Fe^{2+}	1.272	1.294	1.179	1.112	1.104	1.582	1.900
	Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	M1–M3	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Octahedral	Ca	0.234	0.232	0.311	0.590	0.742	1.678	1.640
M4	Na	1.678	1.603	1.604	0.232	1.021	0.275	0.269
	Fe^{2+}	0.085	0.163	0.081	1.153	0.235	0.042	0.086
	Mn	0.002	0.001	0.003	0.025	0.002	0.006	0.006
	Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	M4	2.000	2.000	2.000	2.000	2.000	2.000	2.000
A site	Na	0.160	0.197	0.079	0.152	0.205	0.242	0.571
	K	0.012	0.009	0.007	0.013	0.023	0.016	0.033
Total	A site	0.172	0.206	0.086	0.164	0.227	0.259	0.604
$Fe^{2+}/(Fe^{2+} + Mg)$		0.389	0.393	0.364	0.378	0.329	0.355	0.455
$Mg/(Mg + Fe^{2+})$		0.611	0.607	0.636	0.622	0.671	0.645	0.545
No. of analyses		12	9	10	14	6	6	10

Note: Formulae were normalized to 23-oxygen basis, and all Fe was assumed to be FeO. All analyses are from sample no. VTPI.
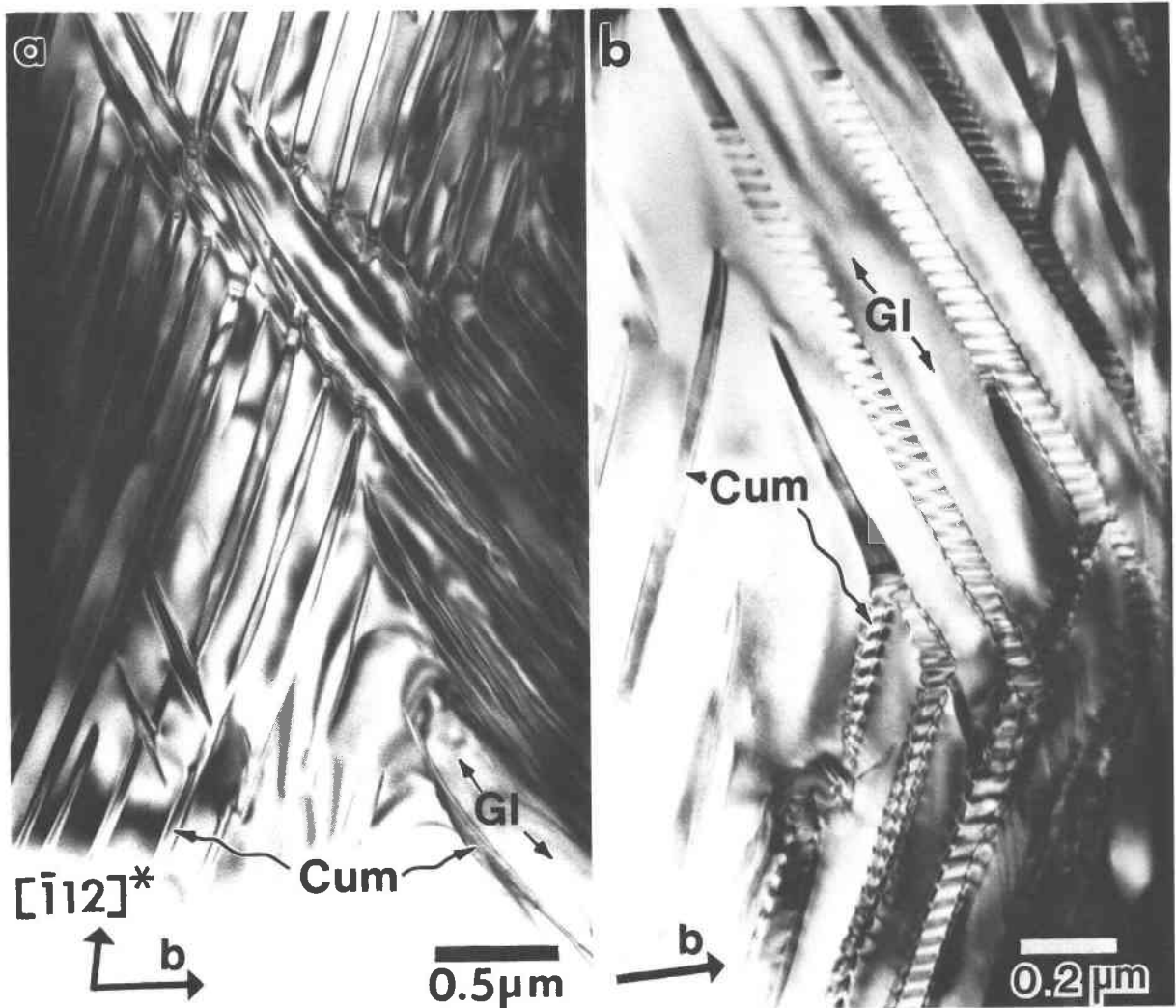
Fig. 2. Bright-field TEM image of cummingtonite exsolution lamellae in glaucophane. (a) Lamellae at area 1 in Fig. 1; the electron beam is parallel to [201] of the host. (b) Cummingtonite lamellae in glaucophane from a previous ion-milling of the same sample. Some of these lamellae have exsolved narrow, periodic (100) lamellae of actinolite. The electron beam is nearly parallel to [101] of the host.

Fig. B-6 in Laird and Bothner, 1986) and has not yet been recognized in our samples from around Tillotson Pond.

Glaucophane

Glaucophane occurs as discrete grains that are the host for both cummingtonite and winchite lamellae as described above, as well as being unexsolved in some areas. Table 1 shows average compositions for each of these modes of occurrence. The compositional differences between exsolved and unexsolved glaucophane are small, suggesting that before the onset of exsolution, the glaucophane was chemically zoned, containing areas enriched in Fe-Mg and Ca. When exsolution began, precipitation of highly calcic cummingtonite occurred in the Fe-Mg–rich zones, and the zones richer in Ca developed winchite lamellae, while other areas remained homogeneous. In

most cases, the highly calcic cummingtonite lamellae developed secondary (100) lamellae of actinolite.

Actinolite

Laird and Albee (1981a) and Laird and Bothner (1986) reported calcic amphiboles from this locality ranging continuously from actinolite to hornblende. In this particular sample, discrete grains of actinolite have been observed (Fig. 1, area 3). Figure 4 shows a conventional TEM image of the thin edge of area 3 (see arrow in Fig. 1) containing intergrown actinolite and hornblende. HRTEM images show the two minerals to be coherently intergrown with the grain boundary at a low angle to the plane of the specimen (Fig. 4).

The average composition of this actinolite is shown in Table 1. The Mg/(Mg + Fe^{2+}) ratio in the actinolite is
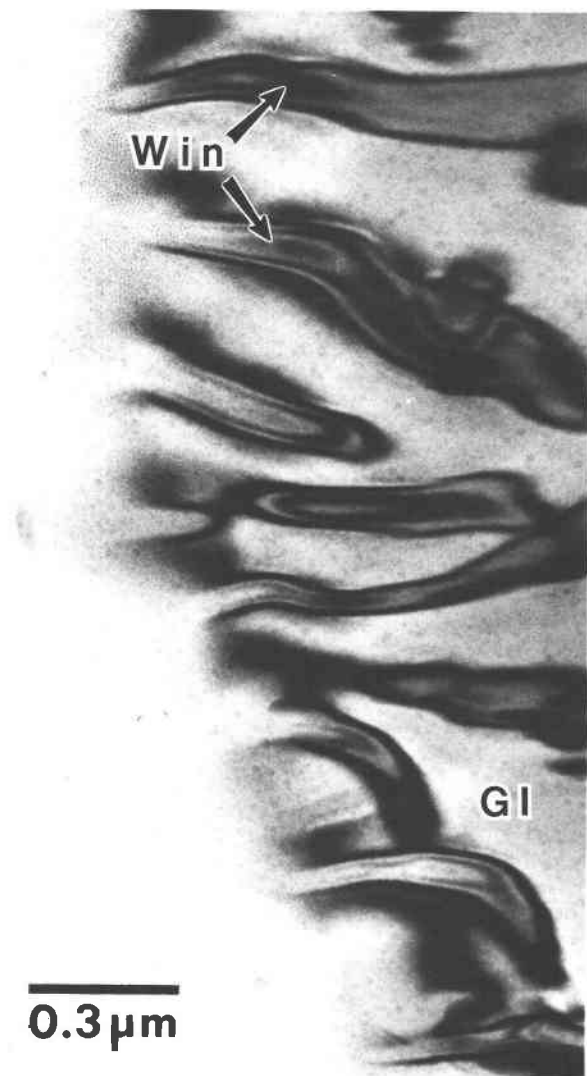
Fig. 4. Bright-field TEM image of thin edge of calcic amphibole inclusion shown in Fig. 1 (area 3, hollow arrow). The actinolite and hornblende are coherently intergrown. The grain boundary is at a low angle to the plane of the specimen and runs from lower left to upper right between the arrows. The electron beam is parallel to [012] of the amphibole.

Fig. 3. Bright-field TEM image of winchite lamellae in glaucophane at area (2) in Fig. 1. The lamellae are much narrower than they appear, owing to a highly tilted orientation. Note the curved nature of the lamellae. An off-zone orientation was used to enhance the contrast.

about 0.645, which is similar to that of the glaucophane, cummingtonite, and winchite. The actinolite appears to be quite homogeneous. As noted above, actinolite also occurs as periodic (100) exsolution lamellae in cummingtonite (Fig. 2b).

Hornblende

The average composition of the hornblende intergrown with actinolite (Fig. 4) is shown in Table 1. The Mg/(Mg + Fe^{2+}) ratio of the hornblende is smaller (0.545) than that of the actinolite, which is consistent with other reports of coexisting actinolite-hornblende (Robinson et al., 1982). The apparent high A-site occupancy of this hornblende may result from the normalization scheme used, which assumes all Fe to be present as FeO. The observed coherent intergrowth between actinolite and hornblende is consistent with a miscibility gap between these two calcic amphiboles (e.g., Robinson et al., 1982).

THE QUESTION OF EQUILIBRIUM

The compositions of the five amphiboles described above are plotted in terms of their M4 site occupancies in Figure 5. The miscibility gaps among sodic, sodic-calcic, ferromagnesian, and calcic amphiboles are clearly displayed by these compositions. The compositional gap between actinolite and hornblende is not evident in terms of M4 occupancy but may be seen by several other plots (e.g., [4]Al vs. Mg/Fe ratio; see Robinson et al., 1982).

Laird and Albee (1981b) have shown that the complex intergrowth and zoning relationships among coexisting amphiboles in these rocks represent distinct periods of mineral growth under different conditions of pressure and temperature. Most likely the five coexisting amphiboles described here do not represent an equilibrium assemblage. It appears from the observed microstructures that the homogeneous glaucophane and exsolved glaucophane plus associated lamellae at the core of this composite grain probably grew and perhaps exsolved during an earlier
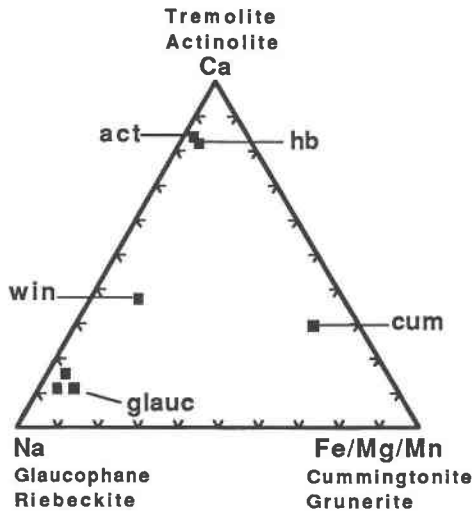
Fig. 5. Plot of M4 occupancy for the five different amphiboles in the composite grain. The miscibility gaps among sodic, sodic-calcic, ferromagnesian, and calcic amphiboles are clearly shown. The gap between actinolite and hornblende is not reflected by M4 content.

period of metamorphism than the homogeneous calcic amphiboles that make up the margins of the composite grain. The calcic amphibole inclusion (Fig. 1, area 3) also may belong to the later period of mineral growth and was connected to the rim grains prior to sample preparation. Although the five coexisting amphiboles may not compose a true equilibrium assemblage, it is likely from the intergrowth textures and the fundamental control of amphibole miscibility gaps by the M4 site (e.g., Robinson et al., 1982) that they represent five mutually immiscible compositions.

CONCLUSIONS

Previous reports of exsolution in sodic amphiboles have involved rocks from rather unusual geologic environments. The exsolved pair of Klein (1966, 1968), consisting of manganoan cummingtonite and magnesioriebeckite, is from the Wabush Iron Formation, southwestern Labrador. Ghose et al. (1974) reported exsolution in a Mn-rich alkali amphibole resulting in lamellae of magnesiorichterite and magnesioriebeckite. These amphiboles are from an unusual mineral assemblage found in the manganese mines at Tirodi, Madhya Pradesh, India. Kimball and Spear (1984) reported intergrown riebeckite and cummingtonite from the Jackson County Iron Formation, Wisconsin, that may have resulted from alteration modified by exsolution.

This paper and Smelik and Veblen (1988) are the first reports of exsolution in "normal" glaucophane, which is the characteristic amphibole found in high-pressure metamorphic rocks such as blueschists and eclogites. In addition, this five-amphibole assemblage differs significantly from most reported multiple-amphibole assem-

blages in that it contains sodic and sodic-calcic amphiboles. Finally, the results presented here indicate that amphiboles that appear optically homogeneous may, in fact, be exsolved on a submicroscopic scale.

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