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# Petrology of a Georgia Blue Ridge amphibolite unit with hornblende + gedrite + kyanite + staurolite

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## ABSTRACT

The Laurel Creek amphibolite is composed of subsets of the assemblage hornblende + chlorite + garnet + kyanite + staurolite + orthoamphibole + plagioclase ($An_{47}$–$An_{97}$) + quartz + ilmenite + rutile + pyrrhotite. Low-variance assemblages provide a relatively complete view of a rare amphibolite facies type. These rare assemblages are believed to be the result of high-pressure metamorphism at moderate temperatures, not of unusual bulk compositions. Laurel Creek amphibolites containing kyanite, staurolite, and gedrite have Mg-rich, olivine-normative basaltic compositions. Mass-balance calculations indicate that the bulk compositions of these rocks can produce common amphibolite assemblages under appropriate conditions. The assemblage hornblende + staurolite (or + kyanite) has previously been demonstrated to be in reaction relation with the assemblage hornblende + plagioclase + epidote + chlorite (and/or garnet), the common amphibolite assemblage in medium-pressure metamorphic terranes. The assemblages hornblende + chlorite + epidote + plagioclase and hornblende + garnet + epidote + plagioclase are graphically demonstrated to be compatible at the same conditions that hornblende coexists with aluminous phases for Mg-rich and Fe-rich bulk compositions, respectively. However, the common low-variance assemblage hornblende + chlorite + garnet + epidote + plagioclase is precluded by the coexistence of hornblende + kyanite. We also demonstrate that the latter assemblage is in reaction relation with gedrite + anorthite, hornblende + gedrite + kyanite, hornblende + corundum, and hornblende + anorthite. Garnet-biotite geothermometry indicates a temperature of 540–625 °C for both adjacent pelitic schists and the Laurel Creek amphibolite. Garnet + kyanite + quartz + ilmenite + rutile equilibrium in the Laurel Creek amphibolite indicates a minimum pressure of 7.7 kbar. The coexistence of hornblende + kyanite + staurolite + gedrite + plagioclase ($An_{88}$–$An_{97}$) in mafic rocks indicates unusual metamorphic conditions. Geothermobarometry from Laurel Creek, as well as other field and experimental data, indicates that amphibolites bearing kyanite-staurolite + hornblende result from a pressure higher than that appropriate for the common amphibolite assemblage.

## INTRODUCTION

Amphibolites of the Laurel Creek Mafic-Ultramafic Complex in northeastern Georgia display a rare amphibolite facies type, composed of (hornblende + quartz)-bearing subsets of the assemblage orthoamphibole + plagioclase + staurolite + kyanite + garnet + chlorite. These unusual amphibolites have olivine-normative basaltic compositions (Table 1). Selverstone et al. (1984) suggested that rocks of basaltic composition stabilize hornblende + staurolite (and/or kyanite) at pressures higher than those appropriate for the stability of the common amphibolite assemblage calcic amphibole + plagioclase + epidote + chlorite + garnet (Laird, 1980; Thompson et al., 1982); results presented here, as well as other field and experimental work (Cooper, 1980; Ward, 1984; Hellman and Green, 1979), corroborate their suggestion.

This study was undertaken to determine whether Laurel Creek amphibolite assemblages resulted from unusual bulk rock compositions or from unusual physical conditions. The significance of hornblende + kyanite + staurolite stability is important to the understanding of the evolution of the Blue Ridge metamorphic province of the Southern Appalachians. The coexistence of hornblende with aluminous silicates (or corundum) is relatively rare in most barrovian metamorphic terranes. Its occurrence is, however, relatively widespread in mafic-ultramafic complexes in the portion of the Blue Ridge province east of the Hayesville fault, along the Georgia–North Carolina

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border (McElhaney and McSween, 1984; K. Walter, in prep.; Pratt and Lewis, 1905). The stability of the unusual assemblage can place a tight constraint on the tectonic environment in which these mafic-ultramafic bodies were emplaced.

## GEOLOGIC SETTING

The Laurel Creek Mafic-Ultramafic Complex, Rabun County, Georgia Blue Ridge, is located approximately 5 km northwest of the Brevard zone and 15 km northeast of the Tallulah Falls dome (Hatcher, 1971; McSween and Hatcher, 1985). The complex is one of several ultramafic and mafic-ultramafic complexes forming a continuous northeast-striking belt in the eastern Blue Ridge (Misra and Keller, 1978). The unit is tens of meters in width and extends approximately 5 km along strike (Fig. 1). The unit was thrust over the Tallulah Falls Formation along a premetamorphic fault and may be ophiolitic in origin (Petty, 1982). The Tallulah Falls Formation (late Precambrian?), composed dominantly of metagraywackes, amphibolites, and subordinate amounts of pelitic schists (Hatcher, 1971), may be time-equivalent with the Ocoee Supergroup (Hatcher, 1972; Hadley, 1972). This formation unconformably overlies 1200-Ma Grenville basement around the flanks of the Tallulah Falls dome.

The southern Blue Ridge is a barrovian metamorphic terrane (Carpenter, 1970), and Laurel Creek is located in the kyanite zone, characterized by the pelitic assemblage kyanite + garnet + biotite. Staurolite is stable only in the absence of muscovite. This zone is flanked 3.5 km to the northwest by a sillimanite isograd, to the southeast by the Brevard fault, and farther to the south by a garnet and chlorite zone (Hatcher, 1971).

## METHOD OF STUDY

More than 100 thin sections were prepared from various rock types from the Laurel Creek area. Phases from 11 amphibolite and 5 pelite samples were analyzed with an automated MAC 400S electron microprobe, using natural and synthetic standards operating at an accelerating voltage of 15 kV. A beam current of 0.03 $\mu$A and a beam diameter of ~10 $\mu$m were used to analyze amphibole, biotite, and plagioclase. All other phases were analyzed with a beam current of 0.05 $\mu$A and a beam diameter of 1 $\mu$m. Correction procedures were those of Bence and Albee (1968) but utilized the data of Albee and Ray (1970).

Silicates were normalized on the basis of the appropriate number of oxygens. All Fe in garnet, chlorite, orthoamphibole, staurolite, and biotite was assumed to be $Fe^{2+}$. Staurolite compositions were normalized to 23 oxygens consistent with a half unit cell of 22 oxygens plus 2 (OH−) groups (Griffin and Ribbe, 1973; Pigage and Greenwood, 1982). FeO total and $Fe_2O_3$ for hornblende L-75 and L-79 were analyzed by a titrimetric procedure. The average Fe contents of hornblende measured by the microprobe varied less than 2% (relative) from the value determined by wet chemistry. In accordance with wet-chemical data, $Fe^{3+}$ of hornblende was calculated by assuming ~89% FeO. The amount of error involved in this assumption for other amphiboles is uncertain.

TABLE 1. Bulk compositions of Laurel Creek amphibolites and norm calculations

| | L-112-D | L-112-N | L-100 | L-79 |
|---|---|---|---|---|
| $SiO_2$ | 48.76 | 47.75 | 44.43 | 47.27 |
| $TiO_2$ | 0.51 | 0.43 | 1.94 | 0.66 |
| $Al_2O_3$ | 13.41 | 15.62 | 16.54 | 13.81 |
| $Fe_2O_3$ | 2.72 | 2.85 | 2.56 | 2.24 |
| FeO | 9.68 | 7.95 | 12.59 | 10.77 |
| MgO | 13.42 | 12.41 | 9.28 | 12.54 |
| MnO | 0.23 | 0.22 | 0.26 | 0.23 |
| CaO | 8.99 | 9.57 | 9.37 | 9.42 |
| $Na_2O$ | 1.35 | 1.53 | 1.64 | 1.55 |
| $K_2O$ | 0.11 | 0.13 | 0.18 | 0.15 |
| $P_2O_5$ | 0.07 | 0.06 | 0.23 | 0.10 |
| Total | 99.25 | 98.52 | 99.0 | 98.59 |
| | | CIPW norm | | |
| Orth | 0.65 | 0.77 | 1.06 | 0.89 |
| Ab | 11.42 | 12.95 | 13.88 | 13.12 |
| An | 30.21 | 35.37 | 37.24 | 30.28 |
| Di | 10.73 | 9.42 | 6.34 | 12.83 |
| Hp | 35.00 | 26.18 | 16.92 | 22.67 |
| Ol | 6.04 | 8.75 | 15.64 | 14.23 |
| Il | 0.97 | 0.82 | 3.68 | 1.25 |
| Mt | 3.94 | 4.13 | 3.71 | 3.25 |
| Ap | 0.39 | 0.14 | 0.53 | 0.23 |

Bulk chemical analyses were obtained with an ORTEC EG&G tube excited X-ray fluorescence analyzer using U.S. Geological Survey rock standards (Flanagan, 1976). Samples were pulverized in a tungsten carbide shatter box and pressed into pellets. FeO and $FeO_{total}$ were determined by a standard titrimetric process. $FeO_{total}$ was within 2% of the value given by XRF analysis.

## ASSEMBLAGES AND MINERAL CHEMISTRY

A diversity of mafic bulk compositions resulted in a variety of amphibolite assemblages. Important low-variance assemblages include Hbl + $An_{97}$ + Ky + St + Ged + Chl + Bt + Qtz + Rut + Po (sample L-112-N), Hbl + $An_{94}$ + Grt + Ged + Chl + Qtz + Rt + Po (L-112-D), Hbl + $An_{90}$ + Grt + St + Chl + Qtz + Ilm + Rt + Po (L-100), Hbl + Ged + Grt + St + Chl + Qtz + Rt + Po (L-79), Hbl + $An_{66-70}$ + Ky + Chl + Bt + Qtz + Rt (L-75), $An_{88-90}$ + Grt + St + Ky + Bt + Qtz (L-36). Locations of samples discussed in the text are shown in Figure 1. Of special note is the coexistence of Hbl + Ged + Ky + St, a mineral association not mentioned in current literature dealing with similar low-variance amphibolites (see Robinson et al., 1982). Laurel Creek amphibolite is dominantly composed of higher-variance subsets of the assemblage Hbl + Pl + Grt + Qtz + Rut + Ilm + Po.

Both calcic and orthoamphiboles are present in the Laurel Creek amphibolite. Amphibole microprobe analyses from important low-variance assemblages are presented in Table 2. Calcic amphibole compositions range from magnesio-hornblende and tschermakitic hornblende to ferroan pargasite (Leake, 1978). Figures 2 and 3 illustrate major amphibole substitutions. Al contents of amphiboles correlate strongly with the presence or ab-

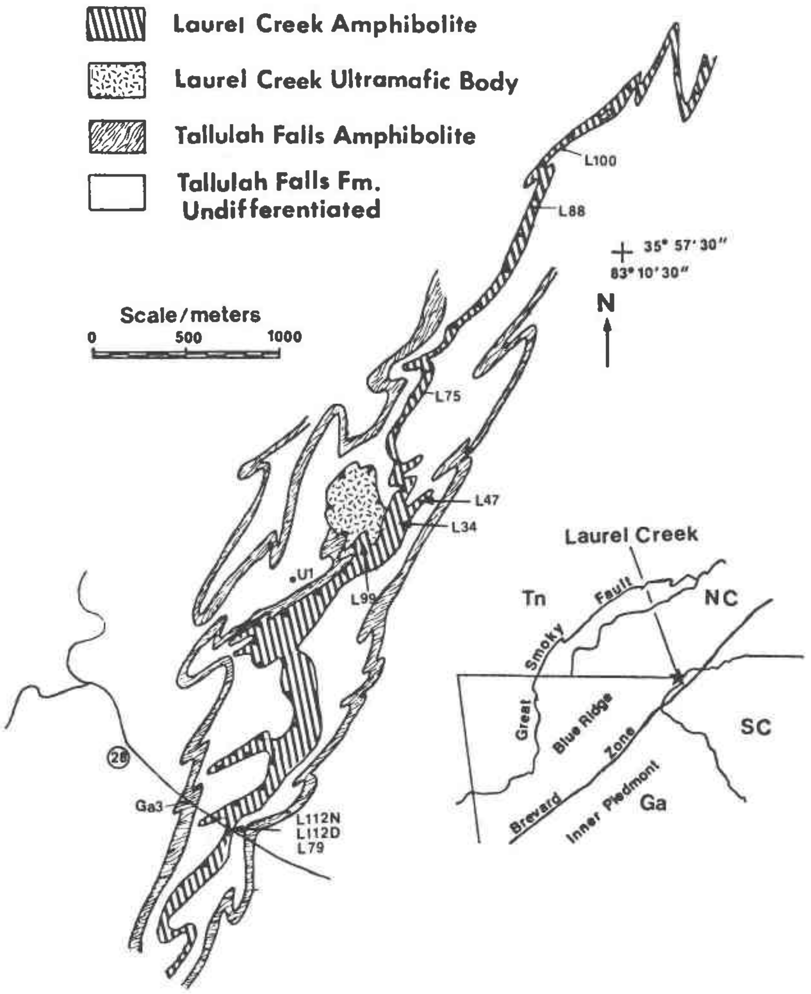

Fig. 1. Location and a generalized geologic map (Petty, 1982) of the Laurel Creek Mafic-Ultramafic Complex.

sence of plagioclase. Figure 3 is a plot of A-site occupancy relative to charge excess in the octahedral sites in orthoamphiboles and calcic amphiboles.

Several studies report the presence of a solvus in orthoamphiboles in both the tschermakitic and edenitic exchanges (Robinson et al., 1971; Stout, 1972; Spear, 1980). No samples from Laurel Creek contain orthoamphibole pairs or visible (400×) exsolution lamellae. Data in Figure 2 imply that a small gap in the amount of total Al exists. When all analyses are considered, there is no discontinuity in the amount of A-site occupancy (edenitic exchange) and octahedral charge excess (tschermakitic exchange approximately) (Fig. 3). Robinson et al. (1971) noted fine exsolution lamellae of gedrite within anthophyllite with widths less than 1.0 $\mu$m. It is possible that extremely fine exsolution lamellae do exist, but have been averaged by a broadly focused electron-microprobe beam. Alternatively, the solvus was never encountered at Laurel Creek.

Plagioclase, ranging in composition from An$_{47}$ to An$_{97}$ (Table 3), is present in all but the most Mg-rich samples. Increase in anorthite component correlates with an increase in the Mg/Fe ratio (Fig. 2) and a decrease in A-site Na of amphiboles. Plagioclase of composition An$_{88-97}$ is confined to low-variance assemblages containing staurolite, kyanite, or gedrite.

Staurolite is present in several samples from the Laurel Creek amphibolite. The Mg/(Mg + Fe) ratio ranges from 0.27 to 0.39 in various assemblages (Table 4). Staurolite grains are fairly homogeneous; however, grains of staurolite included in various phases are more Mg-rich than matrix grains.

Garnet rim compositions contain approximately 55–60% almandine, 22–35% pyrope, 10–13% grossular, and 2–3% spessartine components (Table 4). Garnets from amphibolites and adjacent pelites are fairly homogeneous. However, in amphibolite sample L-100, they are zoned with Fe/Mg decreasing toward the rims. There is no preferred enrichment pattern, however, with respect to Fe and Mg in garnets from different amphibolite samples.

Chlorite is present in both prograde and retrograde as-

TABLE 2. Selected microprobe analyses of amphiboles

| | Calcic amphiboles | | | | | | | Orthoamphiboles | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | L-112-D | L-79 | L-79-A | L-75 | L-75-A | L-112-N | L-100 | L-88 | L-112-D | L-112-N | L-79 |
| $SiO_2$ | 45.02 | 43.36 | 44.29 | 45.04 | 44.63 | 44.77 | 43.45 | 54.72 | 49.79 | 48.46 | 49.27 |
| $Al_2O_3$ | 15.32 | 16.53 | 15.99 | 15.85 | 15.78 | 15.84 | 15.55 | 3.24 | 10.64 | 12.63 | 11.50 |
| $TiO_2$ | 0.39 | 0.34 | 0.39 | 0.52 | 0.48 | 0.39 | 0.53 | 0.08 | 0.13 | 0.15 | 0.17 |
| MgO | 12.77 | 12.2 | 12.61 | 13.09 | 13.00 | 12.77 | 11.13 | 21.41 | 18.66 | 18.67 | 17.83 |
| FeO | 12.03 | 12.48 | 12.27 | 10.93 | 10.76 | 11.39 | 14.28 | 17.70 | 17.17 | 15.84 | 16.78 |
| MnO | 0.11 | 0.04 | 0.07 | 0.14 | 0.22 | 0.28 | 0.11 | 0.53 | 0.47 | 0.60 | 0.36 |
| CaO | 10.93 | 10.75 | 10.64 | 10.2 | 10.37 | 10.59 | 10.2 | 0.56 | 0.62 | 0.67 | 0.58 |
| $Na_2O$ | 1.3 | 1.23 | 1.08 | 1.78 | 1.63 | 1.22 | 1.66 | 0.34 | 1.15 | 0.76 | 0.99 |
| $K_2O$ | 0.2 | 0.2 | 0.17 | 0.2 | 0.21 | 0.21 | 0.2 | n.d. | n.d. | n.d. | n.d. |
| Total | 98.07 | 97.13 | 97.51 | 97.75 | 97.08 | 97.46 | 97.11 | 98.58 | 98.63 | 97.78 | 97.48 |
| | Cations normalized to 23 oxygens | | | | | | | | | | |
| Si | 6.399 | 6.240 | 6.329 | 6.391 | 6.379 | 6.383 | 6.302 | 7.703 | 7.028 | 6.858 | 7.011 |
| $^{IV}Al$ | 1.601 | 1.760 | 1.671 | 1.609 | 1.621 | 1.617 | 1.698 | 0.297 | 0.972 | 1.142 | 0.989 |
| $^{VI}Al$ | 0.966 | 1.045 | 1.023 | 1.042 | 1.038 | 1.046 | 0.960 | 0.241 | 0.799 | 0.966 | 0.941 |
| $Fe^{3+}$ | 0.257 | 0.268 | 0.263 | 0.235 | 0.233 | 0.245 | 0.305 | n.c. | n.c. | n.c. | n.c. |
| Ti | 0.042 | 0.037 | 0.042 | 0.055 | 0.052 | 0.042 | 0.058 | 0.008 | 0.014 | 0.016 | 0.018 |
| Mg | 2.705 | 2.617 | 2.686 | 2.768 | 2.769 | 2.713 | 2.406 | 4.492 | 3.926 | 3.938 | 3.781 |
| $Fe^{2+}$ | 1.030 | 1.034 | 0.987 | 0.899 | 0.907 | 0.954 | 1.271 | 0.259 | 0.262 | 0.081 | 0.260 |
| $Fe^{2+}$ | 0.272 | 0.334 | 0.347 | 0.280 | 0.262 | 0.282 | 0.308 | 1.825 | 1.765 | 1.794 | 1.737 |
| Mn | 0.013 | 0.005 | 0.009 | 0.017 | 0.026 | 0.034 | 0.014 | 0.063 | 0.056 | 0.072 | 0.043 |
| Ca | 1.665 | 1.658 | 1.630 | 1.551 | 1.589 | 1.618 | 1.585 | 0.084 | 0.094 | 0.102 | 0.088 |
| Na | 0.050 | 0.003 | 0.014 | 0.152 | 0.122 | 0.067 | 0.093 | 0.027 | 0.085 | 0.032 | 0.131 |
| Na | 0.038 | 0.340 | 0.286 | 0.337 | 0.328 | 0.271 | 0.374 | 0.066 | 0.230 | 0.176 | 0.142 |
| K | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | n.d. | n.d. | n.d. | n.d. |
| Total | 15.309 | 15.341 | 15.287 | 15.338 | 15.330 | 15.272 | 15.375 | 15.066 | 15.230 | 15.176 | 15.142 |

*Note:* $Fe^{3+}$ calculated; see text for method. n.d. = not detected. n.c. = not calculated.

semblages. Retrograde chlorite occurs in isolated patches of randomly oriented books that are discordant to foliation. Epidote, and less commonly actinolite, are associated with retrograde chlorite. Prograde chlorite has a fine bladed habit that is texturally conformable with adjacent crystals. The prograde nature was verified by regularity in element partitioning among coexisting phases. Chlorite has Mg-rich compositions, with average Mg/(Mg + Fe) = 0.80, and approximately 2.6 formula units of Al (Table 5).

All amphibolite assemblages contain rutile and/or ilmenite. Rutile occurs in Mg-rich samples, whereas ilmenite occurs in Fe-rich samples (Fig. 2).

Fe/Mg enrichment follows the order staurolite ≈ garnet > orthoamphibole > hornblende > chlorite. In three out of four samples, Fe/Mg is greater in staurolite than in coexisting garnet. This is opposite to the $K_D^{Fe}$ normally observed in pelitic schists (Ganguly, 1972; Thompson, 1976). The $K_D^{Fe}$ is close to unity and the apparent reversal

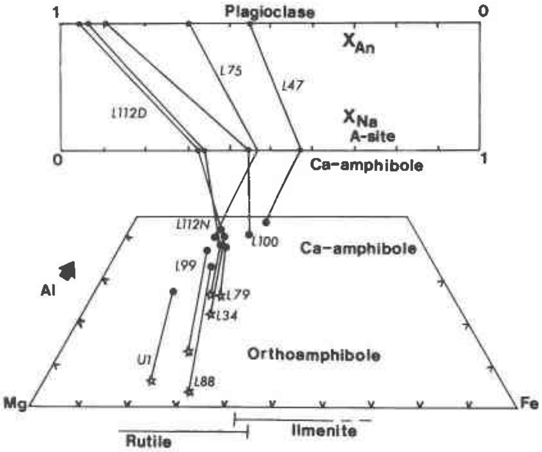

Fig. 2. Al-Fe-Mg plot of amphibole compositions with tie lines connecting calcic amphiboles on the Al-Fe-Mg plane to respective amounts of calculated A-site Na and $X_{An}$ in plagioclase. Also shown is the titanium oxide that coexists with a given assemblage.

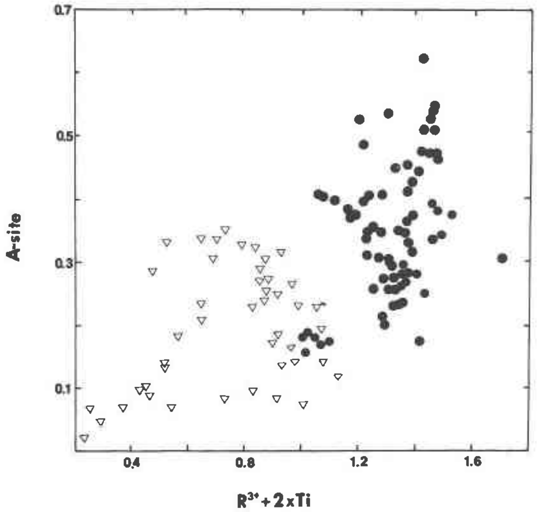

Fig. 3. A-site occupancy vs. the amount of excess charge in the octahedral sites of amphibole. Solid dots are calcic amphibole; open triangles are orthoamphiboles.

TABLE 3. Selected microprobe analyses of plagioclase

| | L-100 | L-112-D | L-36 | L-112-N | L-75 |
|---|---|---|---|---|---|
| $SiO_2$ | 44.81 | 43.68 | 44.29 | 44.55 | 50.54 |
| $Al_2O_3$ | 35.34 | 35.73 | 36.06 | 35.27 | 32.15 |
| $Na_2O$ | 1.14 | 0.36 | 1.06 | 0.63 | 3.80 |
| CaO | 17.91 | 19.27 | 17.61 | 19.27 | 13.59 |
| $K_2O$ | n.a. | n.a. | 0.01 | n.a. | 0.03 |
| Total | 99.20 | 99.04 | 99.03 | 99.72 | 100.11 |
| | Cations normalized to 8 oxygens | | | | |
| Si | 2.078 | 2.037 | 2.055 | 2.063 | 2.321 |
| Al | 1.931 | 1.964 | 1.972 | 1.925 | 1.694 |
| Na | 0.102 | 0.033 | 0.095 | 0.056 | 0.334 |
| Ca | 0.890 | 0.961 | 0.875 | 0.956 | 0.661 |
| K | n.a. | n.a. | 0.000 | n.a. | 0.001 |
| Total | 5.001 | 4.995 | 4.997 | 5.000 | 5.011 |

*Note:* n.a. = no analysis.

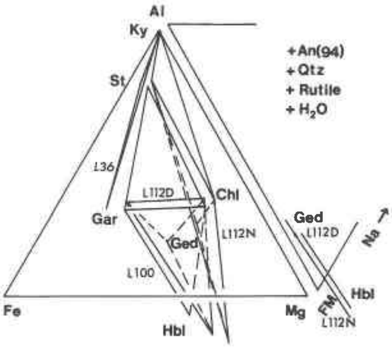

Fig. 4. Diagnostic low-variance assemblages shown on an Al-Fe-Mg-Na anorthite ($An_{94}$) projection.

may reflect analytical uncertainty. However, Ward (1984) and Schreyer et al. (1983) also reported a reversal in $K_D^{Fe}$ for Mg-rich rocks.

## PHASE RELATIONS ON THE Al-Fe-Mg AND Al-Na-(Fe + Mg) PLANES

Laurel Creek amphibolites represent a rare amphibolite facies type. Following the assumptions of Thompson (1957), Harte and Graham (1975), Spear (1978), and Laird (1980), amphibolites can be graphically treated in the simplified system $FeO-MgO-Al_2O_3-CaO-Na_2O$. Ideally, reduction of a system with $(3 + n)$ or $(4 + n)$ components is accomplished by either projection from ubiquitous phases of fixed chemical composition or from phase components having equivalent chemical potential for all assemblages considered (Thompson, 1957; Greenwood, 1975). Considering these guidelines, chlorite is the phase of choice for projection; however, this does not facilitate comparison with mineralogically similar amphibolites (e.g., Spear, 1977, 1978, 1982; Robinson et al., 1982). Low-variance amphibolite assemblages are divided into an anorthite-present and an anorthite-absent group. The latter assemblages are not amenable to projection on the Al-Fe-Mg plane unless amphiboles are used as projection points. In Figure 4, anorthite-present assemblages are projected through anorthite ($An_{94}$) into the Al-Fe-Mg-Na tetrahedron. The measured range in plagioclase composition is $An_{88-97}$. Although hornblende and gedrite are plotted on the Al-Fe-Mg plane, they actually reside off the plane. Their positions relative to Na are shown on the Al-Na-(Fe + Mg) plane. For clarity, only tie lines between the two different types of amphiboles are shown.

The general regularity in cation partitioning argues against gross disequilibrium. Assemblages L-112-D and L-100 exhibit crossing tie lines that suggest either $\mu_{H_2O}$ or $\mu_{An}$ is not equivalent in the two assemblages considered.

TABLE 4. Selected microprobe analyses of garnets and staurolite

| | Garnet | | | | Staurolite | | |
|---|---|---|---|---|---|---|---|
| | L-112-D | L-100 | L-79 | L-36 | L-112-N | L-100 | L-36 |
| $SiO_2$ | 39.20 | 38.80 | 38.30 | 38.20 | 27.60 | 28.40 | 28.05 |
| $TiO_2$ | 0.00 | n.a. | n.a. | n.a. | 0.54 | 0.46 | 0.69 |
| $Al_2O_3$ | 22.40 | 22.90 | 22.90 | 22.10 | 53.76 | 53.80 | 52.57 |
| $Cr_2O_3$ | n.a. | n.a. | n.a. | n.a. | 0.29 | 0.00 | 0.04 |
| MgO | 8.48 | 8.10 | 7.96 | 6.16 | 4.12 | 3.48 | 2.77 |
| FeO | 26.20 | 26.20 | 27.20 | 29.10 | 11.70 | 12.80 | 14.03 |
| MnO | 1.71 | 1.07 | 1.42 | 1.95 | 0.22 | 0.00 | 0.15 |
| CaO | 3.27 | 4.03 | 2.98 | 3.46 | n.a. | n.a. | n.a. |
| ZnO | n.a. | n.a. | n.a. | n.a. | 0.28 | 0.00 | 0.11 |
| Total | 101.26 | 101.10 | 100.76 | 100.97 | 98.51 | 98.94 | 98.41 |
| | Cations normalized to 12 oxygens | | | | Cations normalized to 23 oxygens | | |
| Si | 2.988 | 2.959 | 2.947 | 2.967 | 3.786 | 3.875 | 3.881 |
| Ti | n.a. | n.a. | n.a. | n.a. | 0.052 | 0.044 | 0.069 |
| Al | 2.008 | 2.053 | 2.075 | 2.026 | 8.687 | 8.655 | 8.570 |
| Cr | n.a. | n.a. | n.a. | n.a. | 0.028 | 0.000 | 0.004 |
| Mg | 0.961 | 0.919 | 0.913 | 0.714 | 0.833 | 0.705 | 0.568 |
| Fe | 1.668 | 1.677 | 1.749 | 1.894 | 1.324 | 1.454 | 1.620 |
| Mn | 0.109 | 0.067 | 0.090 | 0.127 | 0.028 | 0.000 | 0.016 |
| Ca | 0.266 | 0.329 | 0.237 | 0.287 | n.a. | n.a. | n.a. |
| Zn | n.a. | n.a. | n.a. | n.a. | 0.028 | 0.000 | 0.008 |
| Total | 8.000 | 8.004 | 8.011 | 8.015 | 14.766 | 14.733 | 14.736 |
| $X_{Mg}$ | 0.366 | 0.354 | 0.343 | 0.274 | 0.386 | 0.327 | 0.260 |

*Note:* n.a. = no analysis.

TABLE 5. Selected microprobe analyses of chlorites and ilmenite

| | Chlorite | | | Ilmenite |
|---|---|---|---|---|
| | L-112-N | L-112-D | L-100 | L-100 |
| $SiO_2$ | 27.37 | 26.12 | 27.27 | — |
| $Al_2O_3$ | 22.90 | 23.92 | 22.47 | 0.16 |
| $Fe_2O_3$ | — | — | — | 14.53 |
| $TiO_2$ | 0.02 | 0.08 | 0.00 | 45.27 |
| MgO | 24.77 | 23.46 | 23.67 | 0.97 |
| FeO | 11.83 | 13.33 | 14.03 | 38.77 |
| MnO | 0.05 | 0.09 | 0.14 | 0.31 |
| Total | 86.93 | 87.00 | 87.58 | 100.02 |
| | Cations normalized to | | | |
| | 14 oxygens | 14 oxygens | 14 oxygens | 3 oxygens |
| Si | 2.696 | 2.596 | 2.698 | — |
| Al | 2.659 | 2.803 | 2.621 | 0.005 |
| $Fe^{3+}$ | — | — | — | 0.276 |
| Ti | 0.001 | 0.007 | 0.000 | 0.859 |
| Mg | 3.637 | 3.475 | 3.491 | 0.037 |
| Fe | 0.974 | 1.108 | 1.161 | 0.818 |
| Mn | 0.001 | 0.007 | 0.000 | 0.005 |
| Total | 9.969 | 9.996 | 9.972 | 2.000 |

*Note:* $Fe^{3+}$ calculated on the basis of stochiometry and chemistry.

Alternatively, combining $Fe^{3+}$ and Al may be an invalid assumption for these amphibolites. Low-variance assemblages reported here contain 2–3% $Fe_2O_3$ (Table 1).

## REACTION RELATION BETWEEN KYANITE AMPHIBOLITES AND THE COMMON AMPHIBOLITE ASSEMBLAGE

Selverstone et al. (1984) noted that staurolite- and kyanite-bearing amphibolites are related by reaction to the common amphibolite assemblage found in medium-pressure metamorphic terranes. A Na-Ca-Al-(Fe + Mg) projection was used to demonstrate this relationship. In this projection, Chl + Grt cannot coexist with Hbl + Ep + Pl as a divariant assemblage. Therefore, combining Fe and Mg obscures a significant portion of amphibolite composition space. Figure 5a is a projection through epidote and quartz into the Fe-Mg-Na-Al tetrahedron. Hbl + Ky, Hbl + St, and Hbl + An do not necessarily prohibit the assemblages Hbl + Chl + Ep + $An_{35}$ or Hbl + Grt + Ep + $An_{35}$ at Mg-rich and Fe-rich compositions, respectively. However, the assemblage Hbl + Chl + Grt + $An_{35}$ + Ep cannot occur with Ky + Hbl. Coexistence of Grt + Chl with Hbl + $An_{35}$ + Ep, though not as common as higher-variance subsets, is nonetheless reported in well-documented medium-pressure metamorphic terranes (Laird, 1980; Harte and Graham, 1975). The preceding results suggest that the bulk-rock Fe/Mg ratio may play a critical role in the presence or absence of staurolite- or kyanite-bearing amphibolites (as well as the common amphibolite assemblage bearing Grt + Chl). Unless the bulk composition is appropriate, typical amphibolite assemblages, such as Hbl + Chl + $An_{35}$ + Ep, can persist in the stability field of Hbl + Ky + St + An. Assemblages such as Hbl + Grt + $An_{47}$ are prevalent at Laurel Creek; however, the five-phase common assemblage is not observed.

Graphical demonstration of the reaction relation between the common amphibolite assemblage and the Laurel Creek amphibolite is accomplished by projecting through chlorite (composition L-79) into the Fe-Na-Ca-Al tetrahedron (Fig. 5b). The composition of chlorite does not vary significantly. Tie lines crossing the plane $An_{35}$ + Ep + Grt (+ Chl) are numerous, indicating that the common amphibolite assemblage containing Chl + Grt cannot occur at physical conditions appropriate to the stability of Hbl + St + Ky + An.

Crossing tie-line relationships observed in Figure 5b are demonstrated more clearly with reactions generated by linear algebra (Braun and Stout, 1975; Greenwood, 1967), as presented in Table 6. Mineral compositions used to balance reactions are also listed in Table 6. All low-variance assemblages at Laurel Creek may be derived from the common amphibolite assemblage by linear combinations of reactions listed in Table 6. These reactions are

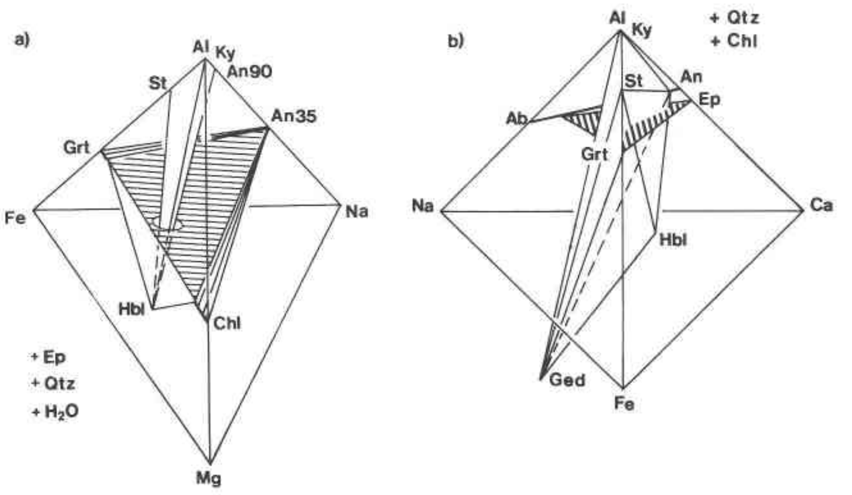

Fig. 5. Some reaction relations in amphibolite space. (a) Al-Fe-Mg-Na diagram; phases are projected through epidote. (b) Al-Fe-Na-Ca diagram; generalized Laurel Creek assemblages are projected through the composition of chlorite (L-79).

TABLE 6. Reactions relating the common amphibolite assemblage to the Laurel Creek amphibolite assemblages

| Common amphibolite assemblage = Laurel Creek assemblages | |
|---|---|
| $4.16Ep + 1.00An_{35} + 0.88Chl + 0.49Grt + 3.42Qtz = 6.87An + 1.31Hbl + 4.30H_2O$ | (1) |
| $1.65Ep + 1.00An_{35} + 1.55Chl + 0.85Grt + 3.16Qtz = 2.82Ky + 2.29Hbl + 4.72H_2O$ | (2) |
| $1.58Ep + 1.00An_{35} + 1.61Chl + 1.34Grt + 3.42Qtz = 0.76St + 2.29Hbl + 4.17H_2O$ | (3) |
| $4.40Ep + 1.09An_{35} + 1.56Chl + 1.00Grt + 8.15Qtz = 9.59An + 1.73Ged + 6.73H_2O$ | (4) |
| $1.00An_{35} + 11.77Chl + 7.45Grt + 36.16Qtz = 11.14Ky + 1.00Hbl + 12.29Ged + 33.77H_2O$ | (5) |
| $1.00An_{35} + 8.88Chl + 6.94Grt + 22.60Qtz = 2.27St + 1.00Hbl + 8.88Ged + 23.35H_2O$ | (6) |
| $0.45An_{35} + 7.55Chl + 4.83Grt + 28.73Qtz = 10.62Ky + 1.00An + 8.38Ged + 21.88H_2O$ | (7) |
| $2.91An_{35} + 4.51Chl + 2.48Grt + 1.00Qtz + 4.79Ep = 8.21Crn + 6.68Hbl + 13.74\ H_2O$ | (8) |

| | |
|---|---|
| Hornblende | $Na_{0.395}Ca_{1.628}Mg_{2.744}Fe_{1.421}Al_{2.744}Si_{6.446}O_{22}(OH)_2$ |
| Chlorite | $Mg_{3.596}Fe_{1.037}Al_{2.582}Si_{2.715}O_{10}(OH)_8$ |
| Staurolite | $Fe_{1.324}Mg_{0.833}Al_{8.686}Si_{3.786}O_{22}(OH)_2$ |
| Anorthite | $Ca_{0.95}Na_{0.05}Al_{1.95}Si_{2.05}O_8$ |
| Garnet | $Fe_{1.935}Mg_{0.84}Ca_{0.247}Al_{2.097}Si_{2.894}O_{12}$ |
| Gedrite | $Na_{0.229}Ca_{0.104}Mg_{3.75}Fe_{2.061}Al_{1.133}Si_{6.887}O_{22}(OH)_2$ |
| Epidote | $Ca_2Al_3Si_3O_{12}(OH)$ |
| Oligoclase | $Ca_{0.2}Na_{0.8}Al_{1.8}Si_{1.2}O_8$ |

consistent with observed high modal volumes of hornblende (approximately 65–90%) and low modal volumes of chlorite ($\ll$2%), garnet ($\ll$10%), and epidote (0%).

The preceding results are consistent with the suggestions of Selverstone et al. (1984); also recognized is the equivalent significance of Ged + An, Hbl + An, Hbl + St + Ged, Hbl + Ky + Ged, and Hbl + Crn. The last assemblage has been noted in several other localities in the Blue Ridge (Pratt and Lewis, 1905; McElhaney and McSween, 1984) and is often associated with kyanite, staurolite, and anorthite.

## BULK-ROCK COMPOSITIONS

XRF and wet-chemical analysis of four samples containing kyanite, staurolite, or gedrite (or all three) reveal Mg-rich olivine-normative basaltic compositions (Table 1). Samples containing kyanite and staurolite are not notably aluminous, and gedrite-bearing samples are not low in Ca. Compositions of Laurel Creek amphibolites are compared on an $(Al + Fe^{+3})_2O_3$–CaO–(Fe + Mg)O diagram (Fig. 6) with compositions of amphibolites from

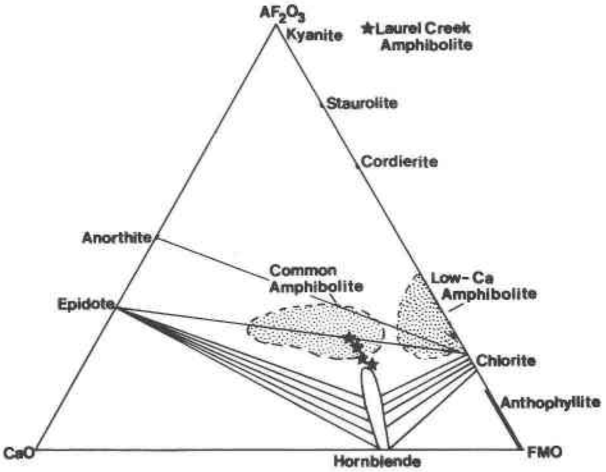

Fig. 6. Plot of measured bulk compositions of unusual Laurel Creek amphibolites on an $(Al + Fe)_2O_3$–CaO–(Fe + Mg)O diagram; also plotted are compositions of common amphibolites from Vermont and of low-Ca amphibolites that bear orthoamphibole.

TABLE 7. Modes (vol%) of Laurel Creek amphibolite and least-squares mass-balance calculations

| | L-100 | L-112-N | L-112-D | L-79 |
|---|---|---|---|---|
| | Modal volumes in Laurel Creek amphibolites | | | |
| Hbl | 78.9 | 80.9 | 66.1 | 81.3 |
| Ged | 0.0 | 0.5 | 13.4 | 5.5 |
| Chl | 0.4 | 0.3 | 1.0 | 0.8 |
| An | 5.9 | tr. | 0.2 | 0.0 |
| Grt | 7.3 | 0.0 | 10.2 | 4.2 |
| St | 3.0 | 2.3 | 0.1 | 3.2 |
| Ky | tr. | 2.9 | 0.0 | 0.0 |
| Qtz | 2.2 | 13.0 | 8.0 | 4.2 |
| Ilm | 0.6 | 0.0 | 0.0 | 0.0 |
| Rt | 1.4 | 0.1 | 1.0 | 0.6 |
| Po | 0.3 | 0.0 | 0.0 | 0.2 |
| Total | 100 | 100 | 100 | 100 |
| | Common amphibolite phases fit to bulk compositions in Table 1 | | | |
| Hbl | 47.2 | 60.9 | 52.3 | 61.8 |
| Chl | 16.5 | 15.8 | 23.5 | 19.1 |
| $An_{35}$ | 8.2 | 10.9 | 6.4 | 7.2 |
| Ep | 14.5 | 4.4 | 5.5 | 1.3 |
| Spn | 0.0 | 1.0 | 1.3 | 1.6 |
| Qtz | 7.7 | 5.1 | 10.4 | 5.8 |
| Ilm | 3.7 | 0.0 | 0.0 | 0.0 |
| Hem | 0.0 | 2.9 | 2.7 | 2.2 |
| Mag | 3.7 | 0.0 | 0.0 | 0.0 |
| Total | 101.4 | 101.1 | 102.1 | 99.0 |
| $(\Sigma\ r^2)^{1/2}$ | 0.000 | 0.000 | 0.645 | 0.370 |

*Note:* $r$ = residual.

| | |
|---|---|
| Hornblende (L-100) | $Na_{0.5}(Ca_{1.8}Fe_{0.2})(Fe_{1.8}Mg_{2.2}Al)(Si_{6.5}Al_{1.5})O_{22}(OH)_2$ |
| Chlorite (L-100) | $FeMg_4Al(Si_3Al)O_{22}(OH)_8$ |
| Hornblende (L-112-N) | $Na_{0.2}(Ca_{1.9}Fe_{0.1})(FeMg_3Al)(Si_{6.8}Al_{1.2})O_{22}(OH)_2$ |
| Chlorite (L-112-N) | $Fe_{1.19}Mg_{3.56}Al_{1.25}(Si_{2.75}Al_{1.25})O_{22}(OH)_8$ |
| Hornblende (L-112-D) | $Na_{0.4}(Ca_{1.9}Fe_{0.1})(Fe_{1.2}Mg_3Al_{0.8})$-<br>$(Si_{6.8}Al_{1.2})O_{22}(OH)_2$ |
| Chlorite (L-112-D) | $Fe_{1.5}Mg_{3.5}Al(Si_3Al)O_{10}(OH)_8$ |
| Hornblende (L-79) | $Na_{0.4}(Ca_{1.9}Fe_{0.1})(Fe_{1.3}Mg_{2.9}Al_{0.8})$-<br>$(Si_{6.8}Al_{1.2})O_{22}(OH)_2$ |
| Chlorite (L-79) | $Fe_{1.55}Mg_{3.45}Al(Si_3Al)O_{10}(OH)_8$ |

*Note:* Plagioclase is always $An_{20}$, epidote is the pure Al end member; sphene and all other phases are pure end-member compositions.

Table 8. Garnet-biotite thermometry

| | Garnet | | | Biotite | | | | |
|---|---|---|---|---|---|---|---|---|
| Sample | Mg/Fe | $X_{Mn}$ | $X_{Ca}$ | Mg/Fe | $X_{Fe}$ | $X_{^{VI}Al}$ | $X_{Ti}$ | $T$ (°C) |
| L-73 | 0.274 | 0.017 | 0.129 | 1.728 | 0.328 | 0.095 | 0.024 | 540 |
| L-77 | 0.232 | 0.112 | 0.076 | 1.255 | 0.364 | 0.130 | 0.038 | 601 |
| L-63A | 0.279 | 0.075 | 0.064 | 1.310 | 0.339 | 0.164 | 0.029 | 625 |
| L-83 | 0.238 | 0.116 | 0.061 | 1.263 | 0.372 | 0.126 | 0.028 | 604 |
| L-47 | 0.341 | 0.056 | 0.117 | 1.780 | 0.300 | 0.135 | 0.024 | 610 |

Table 9. Geobarometry from sample L-100

| Garnet + rutile + kyanite + ilmenite + quartz | | | | |
|---|---|---|---|---|
| $X_{al}$ | $X_{py}$ | $X_{gr}$ | $X_{sp}$ | $a_{al}$* |
| 0.600 | 0.292 | 0.091 | 0.027 | 0.594 |
| $X_{il}$ | $X_{gk}$ | $X_{hm}$ | $a_{il}$** | $P$ (kbar) |
| 0.767 | 0.093 | 0.142 | 0.642 | 7.7 |

* *a* calculated from Newton and Haselton (1981).
** *a* calculated from Andersen and Lindsley (1981).

Vermont that contain the common assemblage (Laird, 1980) and compositions of "low-Ca amphibolites" (Tilley, 1935; Lal and Moorhouse, 1969). All but three of the "low-Ca amphibolites" fall on the (Al + $Fe^{+3}$)$_2$O$_3$–(Fe + Mg)O join. The "low-Ca amphibolites" all lack hornblende, whereas gedrite-bearing Laurel Creek samples always contain high modal quantities of hornblende (~65–90%). Compositions of Laurel Creek amphibolites bearing Ky + St + Ged + An fall within, or very close to, the common amphibolite field.

Bulk compositions of four Laurel Creek amphibolites have been fitted by least-squares calculations to the common amphibolite assemblage Hbl + Chl + An$_{20}$ + Ep + Spn (or Ilm) + Mag (or Hem) + quartz (Table 7). Although these solutions are nonunique, they strengthen the hypothesis that Laurel Creek amphibolites are approximately isochemical with the common amphibolite assemblage. The amounts of normative minerals in these calculated common assemblages are consistent with reactions presented in Table 6. Hornblende occurs in smaller normative amounts in the calculated common assemblage than in Laurel Creek rocks; chlorite, plagioclase, epidote, and sphene are present in greater amounts in the calculated common assemblage than in the rocks.

## CONDITIONS OF METAMORPHISM

Temperatures estimated with the garnet-biotite geothermometer calibrated by Ferry and Spear (1978) vary from 540 to 653 °C (Table 8). The expected range in error reported by Ferry and Spear (1978) is ±50 °C. Garnet-biotite pairs from the Laurel Creek amphibolite (sample

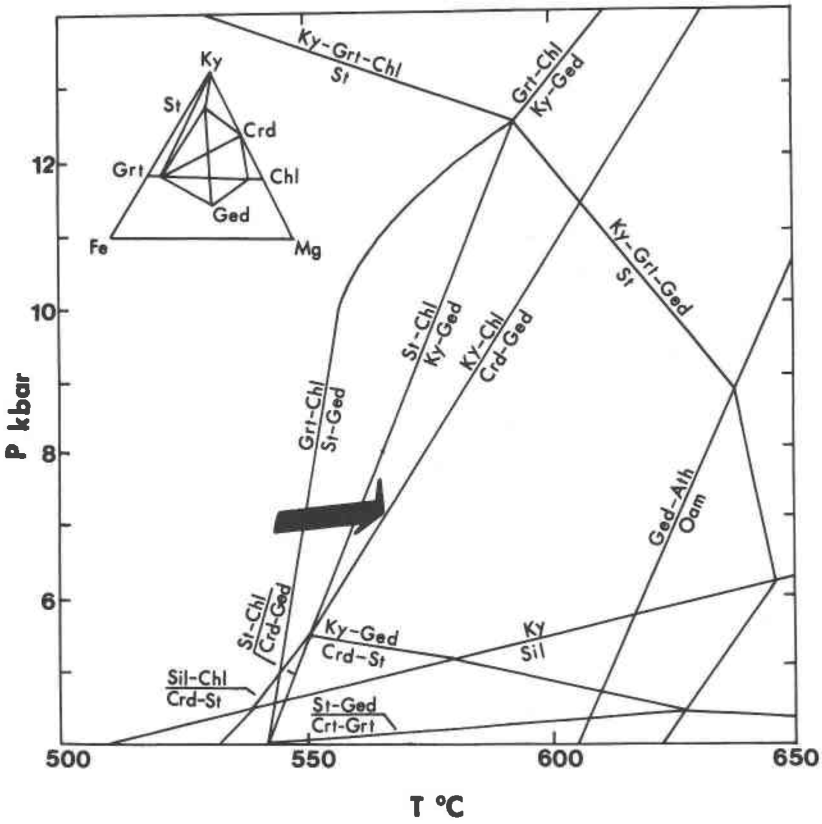

Fig. 7. A portion of the petrogenetic grid of Spear and Rumble (1986).

L-47) and adjacent pelitic schists (all other samples) were used.

The assemblage Grt + Rut + Ky + Ilm + Qtz ("GRAIL"), found in amphibolite sample L-100 (Table 9), indicates a minimum pressure of ~7.7 kbar, at a temperature of 600 °C. This value was inferred from the $K_{eq}$-contoured *P-T* diagram of Bohlen et al. (1983a, 1983b). Sample L-100 contains one crystal of kyanite; because it is almost entirely surrounded by hornblende, it is not interpreted as part of the peak metamorphic assemblage. The assumption that kyanite has an activity of one yields a minimum pressure. The activity of almandine in garnet was calculated according to the model presented by Newton and Haselton (1981); the activity of $FeTiO_3$ in ilmenite was calculated using the model presented by Andersen and Lindsley (1981). There are other mixing models from which the activity of almandine may be calculated that result in significantly different pressures. Ilmenite compositions used for pressure calculation contain approximately 14% (formula units) $Fe_2O_3$, 4% $MgTiO_3$, and $\ll 1\%$ $MnTiO_3$ components (a representative analysis is presented in Table 5). Retrograde oxidation of ilmenite to form hematite and $TiO_2$ could result in an erroneously high calculated pressure. However, ilmenite grains are optically homogeneous, with no signs of hematite exsolution (at 400×), and show very little intra- or intercrystalline compositional variability. The amount of hematite component is also consistent with the ilmenite-hematite *T-X* diagram of Lindsley (1973). The presence of kyanite (Holdaway, 1971) indicates a minimum pressure of 5.7 kbar at 600 °C.

*P-T* conditions measured at Laurel Creek are generally consistent with the petrogenetic grid of Spear and Rumble (1986). The limiting reaction Ky + Chl = Crd + Ged suggests pressures greater than ~5.5 kbar at the estimated temperatures for Laurel Creek. The arrow in Figure 7 passes through the facies series interpreted to be preserved in Laurel Creek assemblages. The persistence of the assemblage St + Chl + Ky + Ged (sample 112N) as well as Grt + Chl suggests local variations in the chemical potential of $H_2O$. The presence of hypersolvus orthoamphiboles at Laurel Creek is not clearly understood in terms of the orthoamphibole critical curve (labeled Ged + Ath = Oam). If fine exsolution lamellae are actually present, then observed assemblages do not reflect peak metamorphic conditions.

## PHYSICAL CONDITIONS OF KYANITE AMPHIBOLITE STABILITY

Kyanite and staurolite almost exclusively occur in metamorphic rocks of pelitic composition; occasionally they occur in metamorphic rocks of mafic composition (e.g., Gibson, 1978; Hellman and Green, 1979; Ward, 1984; Selverstone et al., 1984). On the basis of the observation that the assemblage Hbl + St + Ky is usually present in terranes metamorphosed at pressures greater than 6 kbar (e.g., Cooper, 1980; Ward, 1984; however, see Spear, 1982) at amphibolite-facies temperatures, Selverstone et al. (1984) suggested that it reflects pressures higher than those appropriate to the stability of the common amphibolite assemblage. Data presented here are in agreement with their conclusions.

Experimental studies corroborate this idea. Tholeiitic basalts subjected to 23 kbar at 750 °C (Hellman and Green, 1979), under hydrous conditions, crystallized high-Mg staurolite ($X_{Mg} = 0.57$), kyanite, orthoamphibole, clinopyroxene, and garnet. The assemblage Cpx + Ky + St is the high temperature equivalent of Hbl + Ky + St. Further experimental support for a high-pressure origin for kyanite-bearing amphibolites is given by the experimental and theoretical investigations of Schreyer (1968) and Schreyer and Seifert (1969a, 1969b) in the system $MgO$-$Al_2O_3$-$SiO_2$-$H_2O$, in which it was demonstrated that staurolite (pure Mg end member), pyrope, and "magnesiogedrite" are all important phases at high pressures. It was also predicted (Schreyer and Seifert, 1969b) that Ged + Ky should be stabilized at pressures (~10 kbar) roughly equivalent to those associated with Tlc + Ky "whiteschists" (Scheyer, 1973).

## CONCLUSIONS

The Laurel Creek amphibolite is a rare facies type and does not reflect an unusual bulk composition. The presence of Hbl + St + Ky + Ged + An in a rock of truly basaltic composition indicates that metamorphic conditions affecting the Laurel Creek Complex were different from those for medium-pressure facies series metamorphism (Miyashiro, 1961). Graphical and algebraic treatment of low-variance assemblages at Laurel Creek demonstrates that they are in reaction relation with the low-variance assemblage common to medium-pressure metamorphic terranes.

For relatively Mg-rich compositions, higher-variance assemblages such as Hbl + Chl + Ep + $An_{35}$ are possible, whereas for relatively Fe-rich bulk compositions, Hbl + Grt + Ep + $An_{35}$ can occur at the same grade at which either hornblende coexists with kyanite, staurolite, and anorthite or gedrite coexists with anorthite. Therefore, although temperatures and pressures in a given terrane may be in the stability field of Hbl + Ky + St + An, quite ordinary amphibolite assemblages may persist unless the bulk-rock compositions have the appropriate Fe/Mg ratio (see Fig. 5a).

On the basis of empirical field and laboratory observations, the stability of Hbl + St + Ky appears to be related to higher-pressure metamorphism at temperatures of the amphibolite facies. The experimental work of Hellman and Green (1979) demonstrates reasonably well that staurolite, kyanite, and orthoamphibole are stable in mafic compositions at high pressures. The minimum pressure at which these reactions occur remains uncertain, although the minimum pressure for stability (~6 kbar) suggested by Selverstone et al. (1984) is in agreement with geobarometry at Laurel Creek.

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## REFERENCES CITED

Albee, A.L., and Ray, L. (1970) Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates, and sulfates. Analytical Chemistry, 42, 1408–1414.

Andersen, D.J., and Lindsley, D.H. (1981) A valid Margules formulation for asymmetric ternary solution: Revision of the olivine-ilmenite geothermometer, with application. Geochimica et Cosmochimica Acta, 45, 847–853.

Bence, A.E., and Albee, A.L. (1968) Empirical correlation factors for the electron microanalysis of silicates and oxides. Journal of Geology, 76, 382–403.

Bohlen, S.R., Wall, V.J., and Boettcher, A.L. (1983a) Experimental investigation and geologic applications of equilibira in the system FeO-$TiO_2$-$Al_2O_3$-$SiO_2$-$H_2O$. American Mineralogist, 68, 1049–1058.

——— (1983b) Geobarometry in granulites. In S.K. Saxena, Ed., Kinetics and equilibrium in mineral reactions, p. 141–171. Springer-Verlag, New York.

Braun, G., and Stout, J.H. (1975) Some chemographic relationships in *n*-component systems. Geochimica et Cosmochimica Acta, 39, 1257–1259.

Carpenter, R.H. (1970) Metamorphic history of the Blue Ridge province of Tennessee and North Carolina. Geological Society of America Bulletin, 81, 749–762.

Cooper, A.F. (1980) Retrograde alteration of chromian kyanite in metachert and amphibolite whiteschists from the southern Alps, New Zealand, with implications for uplift on the Alpine fault. Contributions to Mineralogy and Petrology, 75, 153–164.

Ferry, J.M., and Spear, F.S. (1978) Experimental calibration of the partitioning of Fe and Mg between biotite and garnet. Contributions to Mineralogy and Petrology, 66, 113–117.

Flanagan, F.J. (1976) Description and analyses of eight new U.S.G.S. rock standards: U.S. Geologic Survey Professional Paper 840.

Ganguly, J. (1972) Staurolite stability and related parageneses: Theory, experiments and applications. Journal of Petrology, 13, 335–365.

Gibson, G.M. (1978) Staurolite in amphibolite and hornblendite sheets from the upper Seaforth River, central Fiordland, New Zealand. Mineralogical Magazine, 42, 153–154.

Greenwood, H.J. (1967) The *N*-dimensional tie-line problem. Geochimica et Cosmochimica Acta, 31, 465–490.

——— (1975) Thermodynamically valid projections of extensive phase relationships. American Mineralogist, 60, 1–8.

Griffin, D.T., and Ribbe, P.H. (1973) The crystal chemistry of staurolite. American Journal of Science, 273-A, 479–495.

Hadley, J.B. (1972) The Ocoee Series and its possible correlatives. In G.W. Fisher and others, Eds., Studies of Appalachian geology, central and southern, p. 247–259. Interscience Publishers, New York.

Harte, B., and Graham, C.M. (1975) The graphical analysis of greenschist to amphibolite facies mineral assemblages in metabasites. Journal of Petrology, 16, 347–370.

Hatcher, R.D., Jr. (1971) Geology of Rabun and Habersham Counties, Georgia. Geological Survey of Georgia Bulletin 83, 48 p.

——— (1972) Developmental model for the southern Appalachians: Mineral assemblages in metabasites. Journal of Petrology, 16, 347–370.

Hellman, P.L., and Green, T.H. (1979) The high pressure experimental crystallization of staurolite in hydrous mafic compositions. Contributions to Mineralogy and Petrology, 68, 369–372.

Holdaway, M.J. (1971) Stability of andalusite and the aluminum silicate diagram. American Journal of Science, 271, 97–131.

Lal, R.K., and Moorhouse, W.W. (1969) Cordierite-gedrite rocks and associated gneisses of Fishtail Lake, Harcourt Township, Ontario. Canadian Journal of Earth Sciences, 6, 145–165.

Laird, J. (1980) Phase equilibria in mafic schists from Vermont. Journal of Petrology, 21, 1–37.

Leake, B.E. (1978) Nomenclature of amphiboles. American Mineralogist, 63, 1023–1052.

Lindsley, D.H. (1973) Delimitation of the hematite-ilmenite miscibility gap. Geological Society of America Bulletin, 84, 657–662.

Miyashiro, A. (1961) The evolution of metamorphic belts. Journal of Petrology, 2, 277–311.

McElhaney, M.S., and McSween, H.Y., Jr. (1984) Petrology of the Chunky Gal Mountain mafic-ultramafic complex, North Carolina. Geological Society of America Bulletin, 94, 855–874.

McSween, H.Y., Jr., and Hatcher, R.D., Jr. (1985) Ophiolites (?) of the southern Appalachian Blue Ridge. In N.B. Woodward, Ed., Field trips in the southern Appalachians. University of Tennessee Department of Geological Sciences Studies in Geology 9, 144–170.

Misra, K.C., and Keller, F.B. (1978) Ultramafic bodies in the southern Appalachians: A review. American Journal of Science, 278, 389–418.

Newton, R.C., and Haselton, H.T. (1981) Thermodynamics of the garnet-plagioclase-$Al_2SiO_5$-quartz geobarometer. In R.C. Newton, A. Navrotsky, and B.J. Wood, Eds., Thermodynamis of minerals and melts, p. 131–147. Springer-Verlag, New York.

Petty, S.M. (1982) The geology of the Laurel Creek mafic-ultramafic complex in northeast Georgia: Intrusive complex or ophiolite? M. S. thesis, Florida State University, Tallahassee, 147 p.

Pigage, L.C., and Greenwood, H.J. (1982) Internally consistent estimates of pressure and temperature: The staurolite problem. American Journal of Science, 282, 943–969.

Pratt, C.F., and Lewis, A.P. (1905) Corundum and the peridotites of western North Carolina. North Carolina Geologic Survey Report, p. 464.

Robinson, P., Ross, M., and Jaffe, H.W. (1971) Composition of the anthophyllite-gedrite series, comparisons of gedrite and hornblende, and anthophyllite-gedrite solvus. American Mineralogist, 56, 1005–1039.

Robinson, P., Spear, F.S., Schumacher, J.C., Laird, J., Klein, C., Evans, B.W., and Doolan, B.L. (1982) Phase relations of metamorphic amphiboles: Natural occurrence and theory. Mineralogical Society of America Reviews in Mineralogy, 9b, 1–211.

Schreyer, W. (1968) A reconnaissance study of the system MgO-$Al_2O_3$-$SiO_2$-$H_2O$ at pressures between 10 and 25 kb.—staurolite. Carnegie Institution of Washington Year Book 66, 380–392.

——— (1973) Whiteschists: A high pressure rock and its geologic significance. Journal of Geology, 81, 735–739.

Schreyer, W., and Seifert, F. (1969a) High-pressure phases in the system MgO-$Al_2O_3$-$SiO_2$-$H_2O$. American Journal of Science, 267-A, 407–443.

——— (1969b) Compatibility relations of the aluminum silicates in the system MgO-$Al_2O_3$-$SiO_2$-$H_2O$ and $K_2O$-MgO-$Al_2O_3$-$SiO_2$-$H_2O$ at high pressures. American Journal of Science, 267, 371–388.

Schreyer, W., Horocks, P.C., and Abraham, K. (1983) High-magnesium staurolite in a sapphirine-garnet rock from the Limpopo belt, Southern Africa. Contributions to Mineralogy and Petrology, 86, 200–207.

Selverstone, J., Spear, F.S., Franz, G., and Morteani, G. (1984) High pressure metamorphism in the S. W. Tauren Window, Austria: *P-T* paths from hornblende-kyanite-staurolite schists. Journal of Petrology, 25, 501–533.

Spear, F.S (1977) Phase equilibria of amphibolites from the Post Pond Volcanics, Vermont. Carnegie Institution of Washington Year Book 66, 613–619.

——— (1978) Petrogenetic grid for amphibolites from the Post Pond Volcanics: Carnegie Institution of Washington Year Book 67, 805–808.

——— (1980) The gedrite-anthophillite solvus and the composition limits of orthoamphibole from the Post Pond Volcanics, Vermont. American Mineralogist, 65, 1103–1118.

——— (1982) Phase equilibria of amphibolites from the Post Pond Volcanics, Mt. Cube Quadrangle, Vermont. Journal of Petrology, 23, 383–426.

Spear, F.S., and Rumble, D. III. (1986) Pressure, temperature and structural evolution of the Orfordville belt, west-central New Hampshire: Journal of Petrology, 27, 1071–1094.

Stout, J.H. (1972) Phase petrology and mineral chemistry of coexisting amphiboles from Telemark, Norway. Journal of Petrology, 13, 99–145.

Thompson, A.B. (1976) Mineral reactions in pelitic rocks: I. Prediction of *P-T-X* (Mg-Fe) phase relations. American Journal of Science, 276, 401–424.

Thompson, J.B. (1957) The graphical analysis of mineral assemblages in pelitic schists. American Mineralogist, 42, 842–858.

Thompson, J.B., Thompson, A.B., and Laird, J. (1982) Reactions in amphibolite, greenschist and blueschist. Journal of Petrology, 23, 1–27.

Tilley, C.E. (1935) Metasomatism associated with greenstone-hornfels of Kenidjack and Botallack, Cornwall. Mineralogical Magazine, 24, 181–202.

Ward, C.M. (1984) Magnesium staurolite and green chromian staurolite from Fiordland, New Zealand. American Mineralogist, 69, 531–540.

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