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PETROLOGY OF THE LAUREL CREEK AMPHIBOLITE,
GEORGIA BLUE RIDGE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Thomas S. Helms

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ABSTRACT

Uncommon amphibolite mineral assemblages of the Laurel Creek Mafic-Ultramafic Complex, Rabun County, Georgia, are believed to be the result of unusual external physical conditions. These assemblages provide a fairly complete view of an amphibolite facies type for this grade of metamorphism. Important low variance assemblages include hornblende + kyanite + staurolite + anorthite + gedrite + chlorite, hornblende + staurolite + garnet + anorthite + chlorite, and hornblende + garnet + anorthite + gedrite + chlorite.

Chemographic treatment of these assemblages in the system $\text{FeO-MgO-Al}_2\text{O}_3\text{-CaO-Na}_2\text{O-SiO}_2\text{-TiO}_2\text{-H}_2\text{O}$ indicates that equilibrium was approached. It is graphically and algebraically demonstrated that assemblages containing either hornblende + kyanite + staurolite + anorthite, hornblende + gedrite + staurolite + kyanite, or gedrite + anorthite are related by reaction to the common amphibolite assemblage, hornblende + epidote + chlorite + garnet + oligoclase. The common assemblage is prevalent in several medium pressure metamorphic terrains. Higher variance assemblages such as hornblende + epidote + oligoclase + chlorite and hornblende + epidote + plagioclase + garnet can coexist at the same conditions that hornblende coexists with kyanite, staurolite, or anorthite. These are common assemblages in medium pressure terrains at upper amphibolite facies conditions. It has been suggested that the presence of hornblende + kyanite + staurolite presents relatively high pressure metamorphism at moderate temperatures.

Garnet-biotite geothermometry indicates that the final temperature of equilibration was $600 \pm 50^{\circ}\text{C}$. The results of geobarometry are ambiguous. The garnet + plagioclase + kyanite + quartz geobarometer indicates a pressure of 5.6 ± 1 kbar, whereas the garnet + kyanite + ilmenite + rutile + quartz geobarometer indicates a minimum pressure of 7-9 kbar.

TABLE OF CONTENTS

CHAPTER	PAGE
1. INTRODUCTION	1
Statement of Problem	1
Geologic Setting	2
Method of Study	6
2. MINERAL CHEMISTRY AND PETROGRAPHY	9
Description of Lithologies	9
Mineralogy and Mineral Chemistry	12
Fe-Mg Enrichment	32
3. CHEMOGRAPHIC ANALYSIS OF THE LAUREL CREEK AMPHIBOLITE AND ITS RELATIONSHIP TO THE COMMON AMPHIBOLITE ASSEMBLAGE AND LOW-CA AMPHIBOLITES	35
Introduction	35
Phase Relations in the System $\text{FeO-MgO-Al}_2\text{O}_3\text{-CaO-Na}_2\text{O-SiO}_2\text{-TiO}_2\text{-H}_2\text{O}$	36
Significance of Staurolite + Kyanite + Hornblende Stability	42
Reaction Relationship of the Common Amphibolite Assemblage to the Laurel Creek Assemblages	44
The Bulk Composition of Laurel Creek Amphibolite	52
Comparison of Phase Relationships to Other Orthoamphibole-Bearing Amphibolites	56
4. GEOTHERMOMETRY AND GEOBAROMETRY	59
Pressure and Temperature Conditions Constrained by Mineral Stabilities	59
Geothermometry	59
Geobarometry	61
5. CONCLUSIONS	66
REFERENCES	68
APPENDIX	77
VITA	83

LIST OF TABLES

TABLE	PAGE
1. Representative Low Variance Amphibolite Assemblages from Laurel Creek	11
2. Hornblende Compositions	15
3. Orthoamphibole Compositions	19
4. Plagioclase Rim Compositions	20
5. Staurolite Compositions from Laurel Creek Amphibolite and Adjacent Pelitic Lithologies	25
6. Garnet Compositions from Amphibolites and Pelites	28
7. Chlorite Compositions	31
8. Reactions Relating the Common Amphibolite Assemblage to the Laurel Creek Amphibolite Assemblages	49
9. Bulk Rock Chemistry of Selected Laurel Creek Amphibolite Samples with Normative Calculations	53
10. Garnet-biotite Thermometry	62
11. Geobarometry	65
A-1. Replicate Analysis of Standard as Unknown With Best Reported Value	79
A-2. Mineral Abbreviations Used in Text	80
A-3. Mineral Compositions Used in Reactions Presented in Table 8	81
A-4. Biotite and Ilmenite Microprobe Compositions Used in Geobarometry and Thermometry	82

LIST OF FIGURES

FIGURE	PAGE
1. Location and Generalized Map of the Laurel Creek Mafic-Ultramafic Complex	3
2. CFM and AFM Amphibole Quadrilaterals	13
3. Plot of Major Amphibole Substitutions in Hornblende . . .	14
4. Plot of Major Amphibole Substitutions in Orthoamphibole .	18
5. Plot of Plagioclase Compositions	22
6. Photomicrographs of Laurel Creek Amphibolite Assemblages in Plane Polarized Light	23
7. Garnet Rim and Core Compositions From Pelitic and Amphibolitic Lithologies	27
8. Chlorite Compositions Plotted in Terms of Molecular Units of Tetrahedral Aluminum Relative to Molecular Units of Octahedral Aluminum	30
9. Mg/Fe Staurolite Is Plotted Against Mg/Fe Garnet	33
10. Projections of Anorthite Present Assemblages	38
11. Anorthite-absent Projections	41
12. Reaction Relationship of Hornblende + Kyanite + Staurolite + Anorthite Assemblages Viewed from Standard Amphibolite Projections	45
13. Laurel Creek Assemblages Projected Through Chlorite, Quartz, and Rutile Into the Tetrahedron Fe-Na-Ca-Al . . .	48
14. ACF Diagram Demonstrates General Bulk Compositional Differences Between Various Amphibolite Types	54
15. Petrogenetic Grid for Orthoamphibole Amphibolites Taken From Spear	58
16. Reactions Bracketing P-T Conditions at Laurel Creek . . .	60
A-1. Sample Location Map for Samples Analyzed With Electron Microprobe and XRF	78

CHAPTER 1

INTRODUCTION

Statement of Problem

Amphibolites of the Laurel Creek Mafic-Ultramafic Complex exhibit an unusual array of mineral assemblages which include hornblende, gedrite, anthophyllite, kyanite, staurolite, plagioclase, chlorite, garnet, talc, biotite, quartz, rutile, and ilmenite. Several assemblages are of low variance and allow a fairly complete view of a facies type for amphibolites of this grade.

Amphibolites similar to those reported here have been classified as low-Ca or orthoamphibole amphibolites by Robinson et al. (1982). Amphibolites containing hornblende + staurolite + anorthite have been tentatively attributed to an aluminous bulk composition (Silverstone et al., 1984). Both propositions are reviewed here in the context of the Laurel Creek amphibolite. The primary focus of this study is to determine the relationship between Laurel Creek amphibolites and the common amphibolite assemblage hornblende + oligoclase + epidote + garnet + chlorite. This is the prevalent low-variance amphibolite assemblage in many medium-pressure facies series metamorphic terrains (Hart and Graham, 1975; Laird, 1980; Laird and Albee, 1981; Thompson et al., 1982). Chemographic analysis of the Laurel Creek amphibolite indicates that regardless of the bulk composition, crossing tie line relationships prohibit the stability of the common amphibolite assemblage. This indicates that physical conditions have at least locally departed from those

commonly associated with medium pressure metamorphism. Selverstone et al. (1984) have suggested that the formation of hornblende + kyanite in rocks of basaltic composition represents high pressure metamorphism at moderate temperatures. This could be an important constraint in interpreting the tectonic evolution of the Blue Ridge Province.

Geologic Setting

The Laurel Creek Mafic-Ultramafic Complex, Rabun County, Georgia, is located in the Blue Ridge province, approximately 5 km northwest of the Brevard Zone and 15 km northeast of the Tallulah Falls dome (Hatcher, 1971, 1976; McSween and Hatcher, 1985). It is one of several ultramafic and mafic-ultramafic complexes forming a continuous north-east-striking belt in the eastern Blue Ridge (Misra and Keller, 1978). This mafic-ultramafic belt is flanked to the west by the Hayesville fault (Hatcher, 1978). Several mafic-ultramafic complexes are interpreted as being tectonically emplaced (Hatcher et al., 1984); however, the amount of structurally conformable mafic rocks also increases east of this fault.

The complex is a narrow unit, tens of meters in width, and extends approximately 3 km along strike (Figure 1). Within the unit are several ultramafic pods containing a complex array of mineral assemblages including talc, olivine, serpentine, anthophyllite, tremolite, chlorite, magnesite, magnetite, and chromite (Petty, 1982).

Petty (1982) conducted a geochemical investigation of amphibolites from the Laurel Creek Complex (Petty, 1982; Hatcher et al., 1984) which

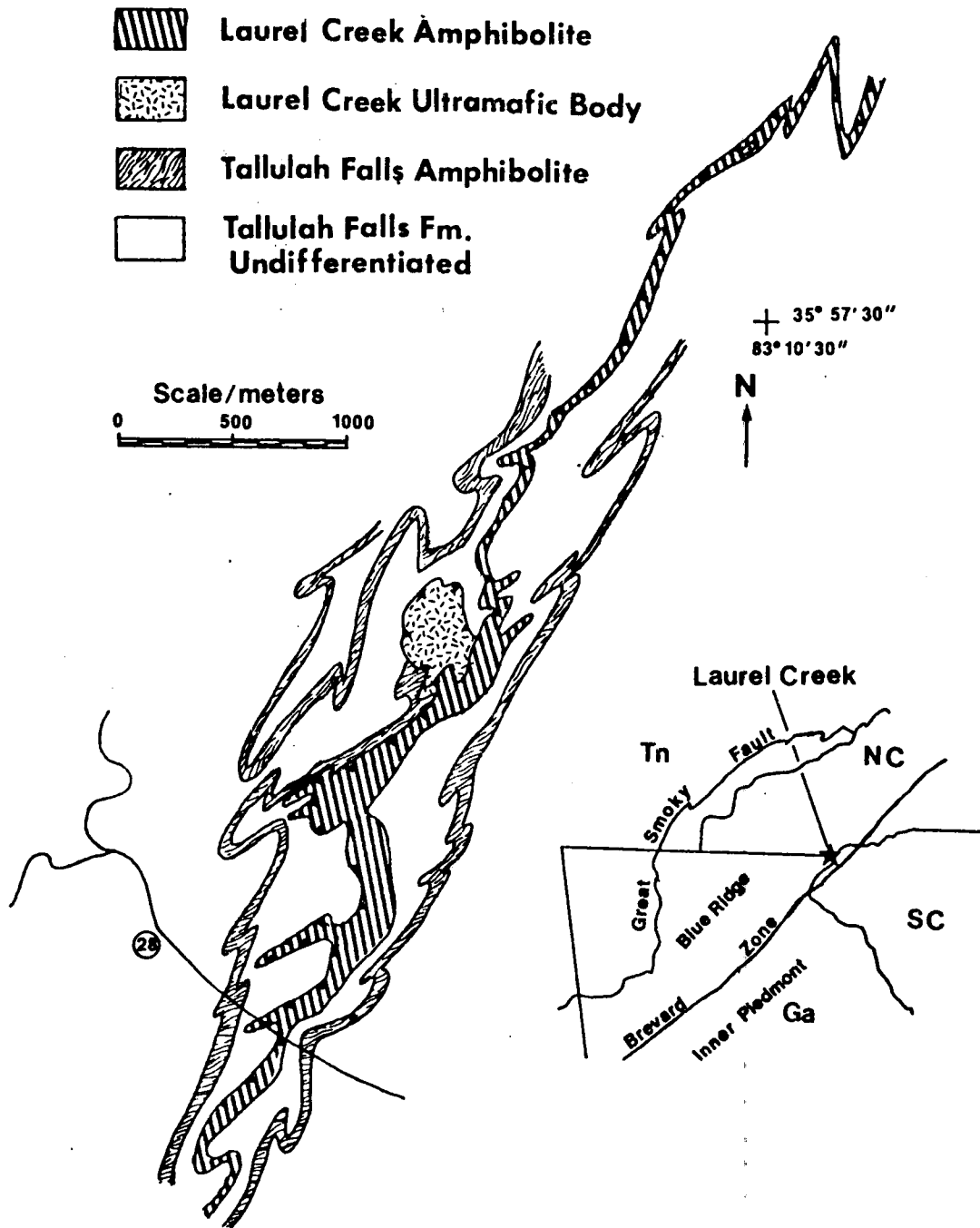


Figure 1. Location and generalized map of the Laurel Creek mafic-ultramafic complex.

was unsuccessful in discriminating a specific tectonic signature for the protoliths. Compositional data were scattered, indicating either element mobility during metamorphism or a cumulate origin. Application of various standard discriminant diagrams did, however, suggest a noncontinental origin.

The complex was thrust onto the lithologies of the Tallulah Falls Formation along a premetamorphic fault (Petty, 1982). The Tallulah Falls Formation is composed dominately of metagreywackes and amphibolites with subordinate amounts of pelitic schists (Hatcher, 1971). The age of the Tallulah Falls Formation protolith is interpreted as late Precambrian and might represent the eastern equivalent of the Ocoee Supergroup (Hatcher, 1972; Hadley, 1972). To the south the Tallulah Falls Formation is correlated with the Sandy Springs Formation and to the north with the Ashe Formation (Hatcher, 1979; Hurst, 1973, Rankin et al., 1973). The Tallulah Falls Formation unconformably overlies 1200 Ma Grenville basement around the flank of the Tallulah Falls dome. The cores of the Tallulah Falls and Toxaway domes contain the only basement rocks (Grenville age) identified in the vicinity (Hatcher, 1973; Hatcher et al., 1979). Amphibolite protoliths in this eastern belt were most commonly tholeiitic basalts (Misra and McSween, 1984). The mafic rocks of the Tallulah Falls Formation have largely gone unstudied. Two samples analyzed by Petty (1982) were quartz normative low-K tholeiites with trace element signatures suggesting a continental affinity. The Tallulah Falls Formation and correlated rocks of the eastern Blue Ridge have been interpreted as forming in a rifted marginal

oceanic or back arc basin (Rankin, 1975; Hatcher, 1978; Raymond and Abbott, 1984).

The southern Blue Ridge is a barrovian metamorphic terrain (Carpenter, 1970). The term barrovian denotes medium-pressure facies series metamorphism (Miyashiro, 1961). Currently very little quantitative data exist to characterize pressure and temperature regimes in the southern Blue Ridge (see, however, Dallmeyer, 1974; Nesbitt and Essene, 1982, 1983; Mohr and Newton, 1983; and Absher and McSween, 1985). The latter study indicates that the Southern Blue Ridge is cored by a Paleozoic granulite facies terrain. Laurel Creek is located in the kyanite zone, characterized by the pelitic assemblage kyanite + garnet + biotite. This zone is flanked 3.5 km to the northwest by a sillimanite isograd and to the southeast by the Brevard Zone. Further to the south a garnet and chlorite zone is truncated by the Brevard Zone (Hatcher, 1971), indicating either a general decrease in temperature from northwest to southeast, or a retrograde overprint associated with the Brevard Shear Zone. The nature of the reaction isograds bounding these zones is not reported.

A Taconian age for peak metamorphism in the Southern Blue Ridge has been determined radiometrically, occurring approximately 480-435 Ma (Glover et al., 1983; Butler, 1972). In the eastern portion of the Blue Ridge, where Laurel Creek is located, a later and milder greenschist event occurred at approximately 380-340 Ma (Hatcher and Butler, 1979). The timing of deformation and peak metamorphism varies within the Blue Ridge (Tull, 1979). The deformation that occurred during the Taconian

Orogeny was largely compressional, apparently related to the closing of a rifted marginal or back arc basin. This event may represent the closing of the Iapetus or proto-Atlantic Ocean (Hatcher, 1978; Cook et al., 1979).

The Laurel Creek area has undergone synmetamorphic deformation with the development of recumbent isoclinal folds that have been refolded into tight upright isoclinal folds. During the development of the upright folds there was no new development of foliation. An apparently isolated narrow band of east-west verging crenulation folds was identified in one outcrop (Petty, 1982). These localized folds are also synmetamorphic. Hatcher (1976) has noted up to five fold-generations in the general vicinity; Laurel Creek, however, is in a belt of consistently northeast-striking, tight-upright isoclinal folds which become deflected around the Tallulah Falls dome. The dominate structural feature in the area is the Tallulah Falls Nappe which may extend as far south as Alabama and as far north as Waynesville, N.C. (Hatcher, 1978).

Method of Study

Over one hundred thin sections were prepared from various lithologies from the Laurel Creek area (sample location map is presented in Figure A-1 in the Appendix). Eleven amphibolite and five pelitic assemblages were analyzed with an automated MAC 400S electron microprobe, using natural and synthetic standards. An accelerating voltage of 15 kV was used. A beam current of 0.03 μ A and a beam diameter of $\approx 10 \mu$ m were used to analyze amphiboles, biotite, and

plagioclase. All other phases were analyzed with a beam current of 0.05 μ A and a beam diameter of 1 μ m. Correction procedures were those of Bence and Albee (1968) utilizing the data of Albee and Ray (1970).

Silicates were normalized on the bases of the appropriate number of oxygens. Ferric iron was calculated for amphiboles on the basis of charge balance considerations. Normalization to 13 cations exclusive of Ca, Na, and K is an unrealistic assumption for calcic amphiboles co-existing with orthoamphibole; under such conditions calcic amphibole should attain maximum saturation of Fe in the M4 site. Normalization to 15 cations exclusive of Na and K often yields reasonable results; however, this procedure assumes no glaucophane substitution. Stout (1972) suggested these two cation normalizations as a means of estimating reasonable maximum and minimum oxidation for calcic amphiboles.

Staurolites have been normalized to 23(O) consistent with with a half unit cell of 22 oxygens and 2 (OH)⁻ groups (Griffin and Ribbe, 1973; also see Pigage and Greenwood, 1981).

Bulk chemical analysis of four low-variance amphibolite samples were carried out on an ORTEC EG&G Tube Excited X-Ray Fluorescence Analyzer using appropriate U.S.G.S. rock standards (Flanagan, 1972). Samples were pulverized to a fine powder in a tungsten carbide shatter box and pressed into pellets. To attain an analysis that most closely represents observed mineral assemblages, the chips from which thin sections were prepared were used for bulk chemical analysis. The mean of replicate analysis of standards as unknowns indicates that major elements are within 6% of best reported values (and typically within 3%); minor

elements are within 10% of best reported values. Replicate analysis are within one standard deviation (see Table A-1 in the Appendix for replicate analysis of standards as unknowns and comparison to best reported values). Fe is assumed to be all ferrous.

CHAPTER 2

MINERAL CHEMISTRY AND PETROGRAPHY

Description of Lithologies

Laurel Creek amphibolites exhibit a variety of textures. The majority of samples are rich in hornblende ($\approx 70-90\%$) and poor in plagioclase and quartz. Some samples are composed completely of hornblende. Locally present are thin leucocratic layers. Nematoblastic or granoblastic texture is well developed depending on the modal quantity of amphibole present. Amphibolites tend to be coarse grained; amphiboles (either hornblende or orthoamphibole) are commonly found as elongate crystals between 1 mm-3 cm in length and up to 2 mm in width. Those rocks rich in hornblende are dark greenish-gray, whereas rocks rich in orthoamphibole have a tan color and are easily mistaken for weathered hornblende-rich amphibolite. Orthoamphibole-rich layers are less common. Also prominent in several layers are large flattened pink garnet porphyroblasts ranging from 1 mm-3 cm in diameter. Garnets are always found in hornblende-rich layers. Euhedral to subhedral staurolite is present in several layers; grain size rarely exceeds 0.5 mm. Crystals of rutile are significant in most samples and can be identified in hand specimen. Grains may attain a width of 0.3 mm and are commonly euhedral.

Amphibolites in the adjacent Tallulah Falls Formation are more leucocratic than those of the Laurel Creek Complex. Commonly these rocks are medium grained and have a gneissic texture composed of thin

($\approx$ 1-5 mm) alternate nematoblastic and granoblastic layers. Hornblende crystals are less than 0.5-1 mm in length. Modal biotite in a number of samples is high enough to impart a schistose texture. Garnet porphyroblasts occur sporadically; however, garnets in these amphibolites are generally less than 2 mm in diameter and commonly have a sieve-like appearance in thin section.

A diversity of mafic bulk compositions found within the Laurel Creek amphibolite results in a wide variety of amphibolite assemblages (Table 1). Important low variance assemblages are (see mineral abbreviations in Table A-2 in the Appendix):

Hbl + An + Ky + St + Ged + Chl + Bi + Qtz + Rut + Po (L-112-N),

Hbl + An + Gar + Ged + Chl + Qtz + Rut + Po (L-112-D),

Hbl + An + Gar + St + Chl + Qtz + Ilm + Rut + Po (L-100),

Hbl + Ged + Gar + St + Chl + Qtz + Rut + Po (L- 79),

Hbl + An(66-70) + Ky + Chl + Bi + Qtz + Rut (L-75),

An + Gar + St + Ky + Bi + Qtz (L-36).

Of special note is the coexistence of hornblende + gedrite + kyanite + staurolite, a mineral association that is not mentioned in current literature (in English) dealing with similar low-variance amphibolites (see Robinson et al., 1982). The Laurel Creek amphibolite is dominantly composed of higher variance subsets of the assemblage hornblende + plagioclase + garnet + quartz + rutile + ilmenite + pyrrhotite. Adjacent amphibolites of the Tallulah Falls Formation are always high-variance subsets of the assemblage hornblende + plagioclase +

Table 1. Representative Low Variance Amphibolite Assemblages from Laurel Creek

Samples	1-112-D	1-112-N	L-100	L-79	L-34	L-75	L-47	Ga-3	U1
Hbl	+	+	+	+	+	+	+	+	+
Plag	An96	An94	An90			An70			
Chl	+	+	+	+	+	+			
Gar	+		+	+			+	+	
Ged	+	+		+	+				
Ky		+	+			+			
St	+	+	+	+	+		(+)		
Anth									+
Epi									
Talc									+
Qtz	+	+	+	+	+	+	+	+	+
Sph									
Ilm			+				+	+	
Rut	+	+	+	+	+	+			+
Po	+	+	+	+	+			+	

Mineral abbreviations are listed in Table A-2 in the Appendix.

garnet + epidote + quartz + sphene + ilmenite + pyrrhotite. In those assemblages containing garnet and epidote, the epidote texturally appears to be a result of a later greenschist event. Sphene is indigenous to the Tallulah Falls amphibolites, whereas rutile is almost always confined to Laurel Creek amphibolite. Rutile is partially enclosed in sphene in one Tallulah Falls sample with the assemblage hornblende + plagioclase + epidote + quartz. Ilmenite is common in both amphibolites.

Mineralogy and Mineral Chemistry

Several studies provide information on the variation of amphibolite mineral chemistry over a range of pressure and temperature conditions. Laurel Creek lithologies provided chemical data for several minerals equilibrating from a variety of bulk compositions at equivalent pressure and temperature.

Both calcic and orthoamphiboles are present in the Laurel Creek amphibolite. Only calcic amphibole is present in the amphibolites of the Tallulah Falls Formation. Calcic amphibole coexists with orthoamphibole over a fairly broad range of compositions (Figure 2). Although coexisting orthoamphiboles of sharply discontinuous compositions were not observed, there is a small break in aluminum and sodium content over a continuous range of Mg:Fe ratios.

Calcic amphibole compositions are presented graphically in Figures 2 and 3; actual rim and core compositions are presented in Table 2. Crystals tend to be homogeneous. Both orthoamphiboles and calcic

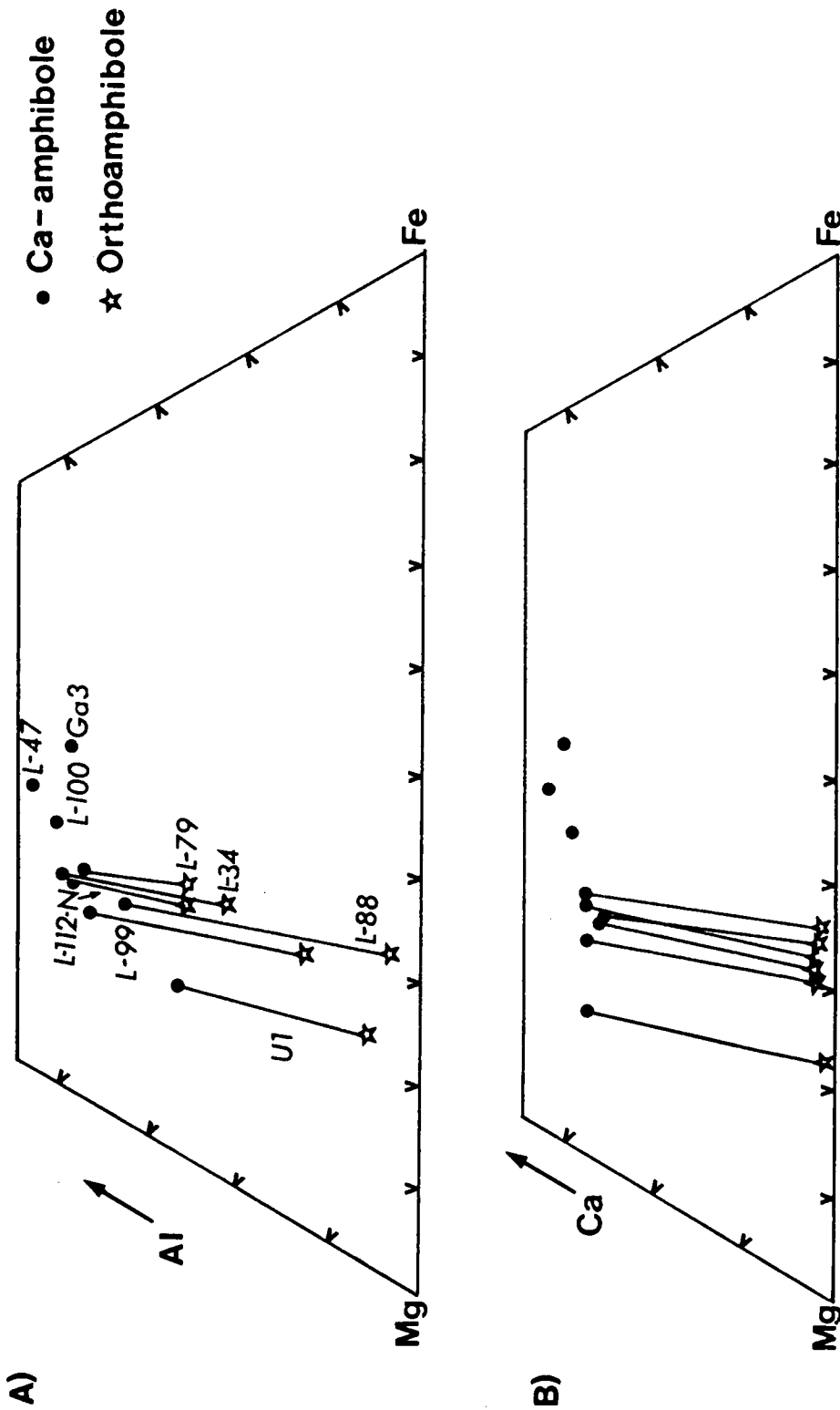


Figure 2. CFM and AFM amphibole quadrilaterals. (A) Calcic-amphiboles and coexisting orthoamphiboles plotted in terms of Fe-Mg-Al. Although no coexisting orthoamphiboles were identified, there does appear to be a discontinuity in Al content over a fairly tight continuum of bulk compositions. (Ga3 is from the Tallulah Falls amphibolite.) (B) A plot of coexisting amphiboles in a "amphibole quadrilateral" Fe-Mg-Al.

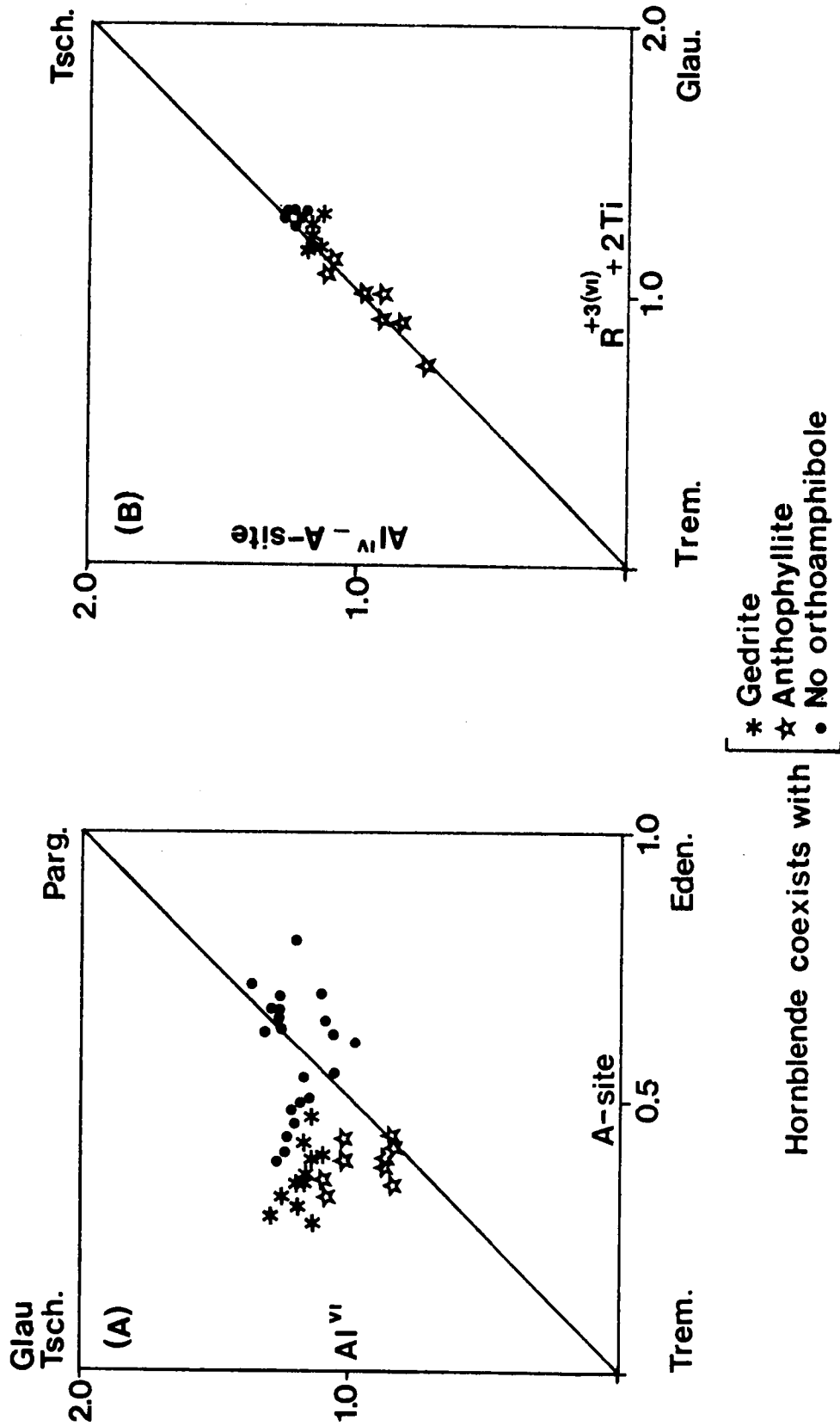


Figure 3. Plot of major amphibole substitutions in hornblende. (A) Plot in molecular proportions of octahedral aluminum against A-site occupancy for hornblende. (B) Plot in molecular proportions of tetrahedral aluminum minus the amount of A-site occupancy against the amount of trivalent ions in the octahedral positions plus twice the amount of Ti.

Table 2. Normblende Compositions

Sample	L-112-B		L-112-W		L-88		L-34		L-99		Ga-3		L-79		L-100		L-47		U-1		L-75	
	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core
SiO ₂	45.02	44.60	44.77	45.40	45.40	44.58	44.60	44.80	45.00	45.20	41.20	40.70	43.40	43.90	43.50	43.10	41.10	41.60	48.50	48.90	44.10	44.70
Al ₂ O ₃	15.50	14.93	15.84	15.10	12.40	11.40	15.90	16.10	14.60	14.50	15.30	15.30	16.50	16.01	15.60	15.70	17.10	17.20	9.64	9.77	16.40	15.90
Cr ₂ O ₃	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
TiO ₂	0.39	0.38	0.39	0.38	0.46	0.46	0.46	0.46	0.34	0.29	0.26	1.43	0.34	0.34	0.33	0.37	0.45	0.48	0.25	0.34	n.d.	n.d.
FeO	12.70	13.20	12.77	13.30	14.20	14.78	13.40	13.50	14.50	14.50	18.40	18.40	12.20	12.50	11.10	11.00	9.18	9.14	16.80	17.30	13.70	14.20
MnO	11.60	12.03	11.39	11.40	11.90	13.06	11.80	11.50	12.50	12.50	15.10	15.10	12.50	12.40	14.30	14.30	16.20	15.90	8.34	8.42	11.00	10.40
Fe ₂ O ₃	0.12	0.11	0.29	0.25	0.21	0.37	0.36	0.16	0.25	0.25	0.20	0.20	0.10	0.09	0.11	0.09	0.18	0.15	0.02	0.14	n.d.	n.d.
CaO	11.10	10.90	10.58	10.40	10.60	9.54	10.40	10.30	10.70	10.60	11.20	10.90	10.80	10.70	10.70	10.60	10.90	10.80	10.70	10.80	10.50	10.40
MgO	1.58	1.48	1.12	1.09	1.34	1.25	1.11	1.05	1.38	1.34	1.87	1.77	1.23	1.08	1.25	1.24	2.09	2.00	1.09	1.06	1.67	1.53
K ₂ O	0.20	0.16	0.19	0.18	0.12	0.13	0.20	0.18	0.15	0.14	0.43	0.42	0.20	0.16	0.20	0.20	0.39	0.43	0.11	0.11	0.17	0.12
Total	98.2	97.8	97.34	97.50	97.30	97.30	97.73	97.40	97.00	97.70	97.40	97.20	97.20	97.10	97.20	97.30	97.80	97.90	96.60	97.73	97.54	97.30

Cations normalized to 23(O)

Si	6.470	6.439	6.455	6.521	6.403	6.717	6.413	6.446	6.484	6.485	6.206	6.157	6.311	6.343	6.345	6.341	6.112	6.146	6.940	6.932	6.353	6.442
Al	1.520	1.561	1.545	1.479	1.397	1.283	1.587	1.554	1.506	1.517	1.794	1.843	1.889	1.817	1.615	1.659	1.888	1.854	1.060	1.068	1.847	1.558
Al	1.064	0.980	1.145	1.077	0.719	0.655	1.103	1.183	0.977	0.927	0.932	0.879	1.147	1.124	1.070	1.059	1.105	1.153	0.556	0.565	1.040	1.042
Cr	0.000	0.000	0.000	0.000	0.072	0.059	0.000	0.000	0.013	0.025	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.128	0.100	0.000	0.000
Fe ³⁺	0.038	0.042	0.008	0.079	0.040	0.055	0.062	0.019	0.044	0.069	0.034	0.016	0.050	0.046	0.045	0.044	0.000	0.000	0.000	0.000	0.000	0.000
Ti	0.042	0.038	0.039	0.038	0.031	0.046	0.046	0.034	0.042	0.042	0.026	0.026	0.034	0.034	0.040	0.040	0.020	0.020	0.025	0.010	0.033	0.030
Mg	2.733	2.846	2.741	2.837	3.080	3.174	2.820	2.779	3.042	3.100	1.983	1.893	2.645	2.705	2.436	2.417	2.034	2.014	0.575	0.575	2.943	2.042
Fe	1.123	1.054	1.013	1.019	1.038	1.011	0.969	0.985	0.882	0.837	2.025	2.052	1.124	1.071	1.369	1.448	1.765	1.730	0.592	0.626	0.674	0.686
Fe	0.281	0.336	0.350	0.325	0.383	0.481	0.384	0.381	0.307	0.345	0.273	0.227	0.347	0.370	0.320	0.292	0.240	0.206	0.276	0.364	0.291	0.327
Mn	0.012	0.011	0.013	0.013	0.015	0.042	0.000	0.020	0.029	0.029	0.000	0.000	0.000	0.000	0.010	0.010	0.020	0.017	0.021	0.010	0.000	0.000
Ca	1.483	1.550	1.513	1.411	1.648	1.477	1.804	1.588	1.552	1.634	1.810	1.772	1.675	1.643	1.600	1.646	1.714	1.714	1.648	1.633	1.597	1.593
Na	0.024	0.003	0.000	0.035	0.000	0.000	0.012	0.011	0.012	0.000	0.000	0.000	0.000	0.000	0.070	0.032	0.026	0.063	0.035	0.000	0.112	0.080
Na	0.134	0.401	0.338	0.303	0.375	0.397	0.308	0.291	0.375	0.375	0.491	0.515	0.348	0.303	0.400	0.442	0.573	0.513	0.238	0.292	0.355	0.345
K	0.034	0.025	0.038	0.029	0.021	0.021	0.034	0.029	0.025	0.021	0.119	0.115	0.034	0.030	0.034	0.034	0.070	0.078	0.017	0.170	0.021	0.021
Total	15.368	15.426	15.339	15.332	15.430	15.418	15.342	15.320	15.400	15.404	15.493	15.629	15.402	15.346	15.430	15.496	15.643	15.591	15.255	15.469	15.376	15.368

Fe⁴⁺ calculated by charge balance.

n.d. = not detected.

amphiboles from the Laurel Creek area can essentially be considered in terms of anthophyllite and tremolite endmembers respectively, removed along the exchanges $A_{Na}^{iv}Al = {}^{iv}Si(A_{vacancey})$ (edenite), ${}^{iv}Al^{vi}Al = {}^{iv}Si^{vi}Mg$ (tschermakite), $M^4Ca = M^4(Mg, Fe, Mn)$, and $M^{1,2,3}Mg = M^{1,2,3}(Fe, Mn)$ (see Thompson, 1982; Thompson et al., 1982). Hornblende compositions generally lie along the tschermakite exchange between 0.8 and 1.4 molecular units and along the edenite exchange between 0.3 and 0.7 molecular units. Those samples coexisting with orthoamphibole are richer in tschermakite component relative to edenite component, and seem to exhibit a net decrease in edenite component (see Figure 2a). The absolute amount of tschermakite component, however, is also less in those samples coexisting with orthoamphibole (see Figure 2b).

The other substitution of significance is $M^4Fe = Ca$ (Fe-anthophyllite component). The range in anthophyllite component is 0.3-0.4 molecular units. In Figure 2b, Al^{iv} minus the amount of Na+K in the A-site is plotted relative to the amount of trivalent ions in $M^{1,2,3}$ plus twice the molecular units of Ti (given the exchange ${}^{vi}Ti^{iv}Al = {}^{vi}Si^{vi}2Mg$). Those samples falling below the line representing the tschermakite exchange vector are due to either glaucophane or riebeckite substitutions. Apparently there is very little of either component. This is likely to be a result of the normalization procedure adopted. Laird and Albee (1981) reported substantially higher amounts of Na^{M^4} for calcic amphiboles of similar grade (approximately 0.3 molecular units). Using their method of normalization similar values can be derived for Laurel

Creek amphiboles. Objection to such a normalization for samples coexisting with orthoamphibole has been stated.

The compositions of orthoamphiboles are graphically presented in Figures 2 and 4; rim and core compositions are presented in Table 3. There is a negative correlation between tschermakite component and edenite component in the more aluminous orthoamphiboles or gedrites (Figure 4a). This must be an effect of bulk composition, given the restricted area from which these samples were collected (i.e., generally equivalent pressures and temperatures of equilibration). Those samples coexisting with plagioclase have the highest A-site occupancy, indicating an overall increase in bulk Na and Ca content resulting in an increase in edenite component.

Several studies have verified the presence of a miscibility gap in orthoamphiboles (Robinson et al., 1972; Stout, 1972; Spear, 1980). No samples contained orthoamphibole pairs or visible exsolution lamellae. The absence of exsolution lamellae may indicate that the solvus was not intersected upon cooling from peak temperature conditions. Alternatively, orthoamphiboles are hypersolvus. Figure 2a shows that a small gap in the amount of total Al actually does exist over a continuum of bulk Fe:Mg compositions. Figure 4a indicates that the solvus is between 0.15 and 0.2 molecular units of A-site occupancy with an asymmetry towards the more aluminous and sodic phase.

Plagioclase, ranging in composition from An₄₇-An₉₇ (Table 4), is present in all but the most Mg-rich samples. Increase in anorthite component correlates with an increase in the Mg:Fe ratio in hornblendes

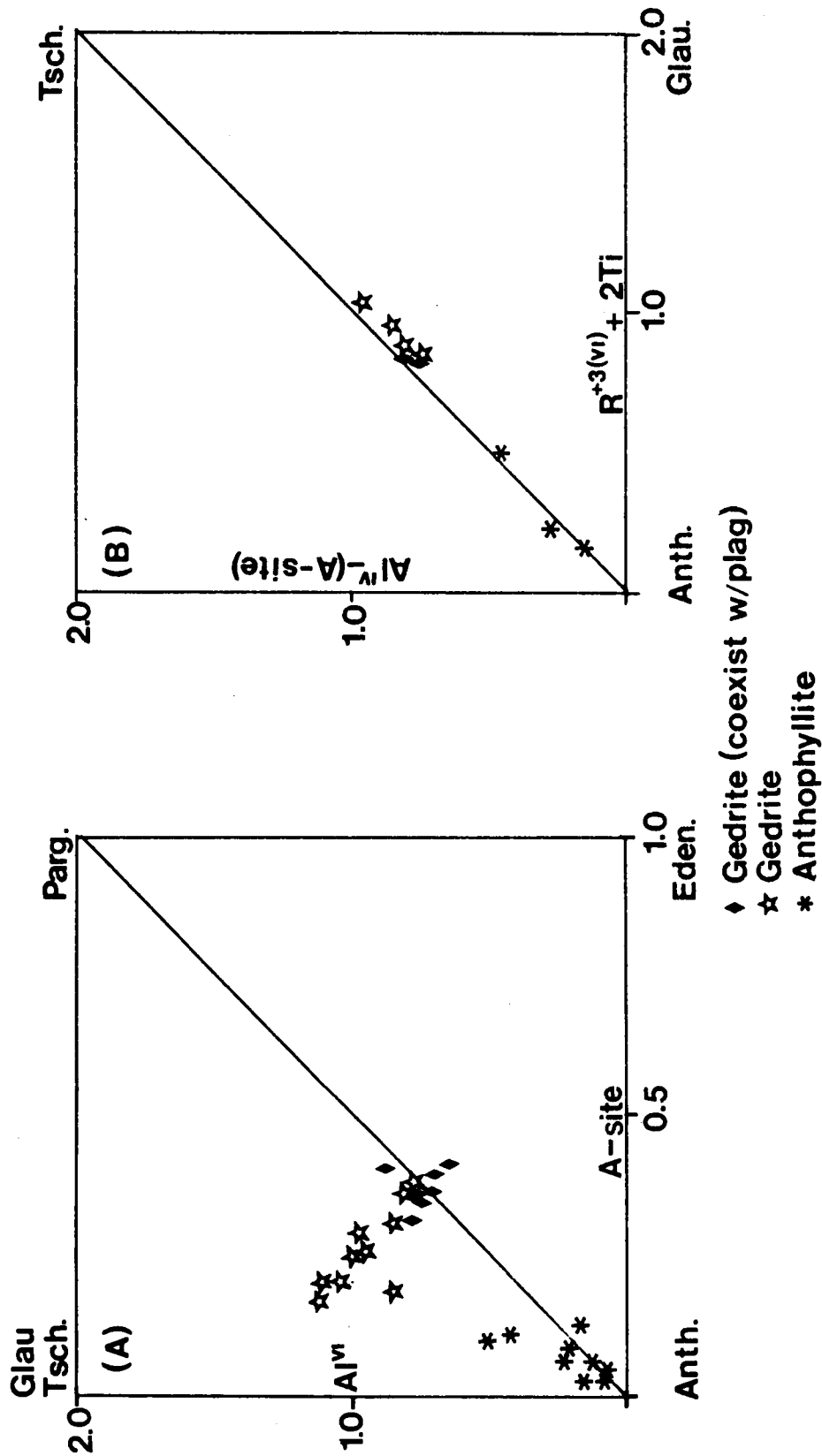


Figure 4. Plot of major amphibole substitutions in orthoamphibole. (A) Plot in molecular proportions of octahedral aluminum against A-site occupancy for orthoamphibole. (B) Plot in molecular proportions of tetrahedral aluminum minus the amount of A-site occupancy against the amount of trivalent ions in the octahedral positions plus twice the amount of Ti.

Table 3. Orthoamphibole Compositions

Sample	L-112-D		L-34		L-99		U-1		L-112-N		L-79	
	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core
SiO ₂	48.10	50.60	47.90	49.60	52.90	52.30	55.73	55.30	48.50	48.42	48.60	49.10
Al ₂ O ₃	10.80	7.98	12.90	11.90	5.85	5.94	2.48	2.83	12.60	13.85	12.80	11.80
TiO ₂	0.18	0.14	0.23	0.21	0.05	0.10	0.09	0.11	0.15	0.16	0.18	0.20
MgO	18.60	20.20	18.60	18.90	21.20	22.10	25.00	24.90	18.70	18.17	17.80	17.70
FeO	17.10	17.50	16.70	16.70	16.30	15.40	13.20	13.30	15.80	15.87	17.40	17.80
MnO	0.48	0.41	0.43	0.44	0.41	0.27	0.36	0.41	0.60	0.57	0.39	0.47
CaO	0.66	0.53	0.71	0.68	0.49	0.56	0.49	0.53	0.67	0.73	0.69	0.63
NaO	1.27	1.30	0.98	0.88	0.41	0.52	0.05	0.23	0.76	0.73	0.92	0.86
Total	97.20	98.70	98.50	99.30	97.60	97.20	97.90	97.60	97.80	97.70	98.70	98.60

Cations normalized to 23(O)												
Si	6.909	7.164	6.763	6.936	7.470	7.407	7.758	7.696	6.853	6.801	6.853	6.944
Al	1.091	0.836	1.237	1.064	0.530	0.593	0.242	0.304	1.147	1.199	1.147	1.056
Al	0.742	0.494	0.913	0.882	0.444	0.396	0.162	0.157	0.957	1.093	0.975	0.920
Fe+3	0.053	0.095	0.121	0.069	0.085	0.046	0.060	0.064	0.066	0.019	0.052	0.028
Ti	0.017	0.012	0.021	0.020	0.004	0.008	0.008	0.008	0.012	0.016	0.016	0.021
Mg	3.988	4.236	3.916	3.922	4.462	4.550	4.770	4.771	3.935	3.804	3.730	3.731
Fe	0.200	0.163	0.029	0.107	0.005	0.000	0.000	0.000	0.030	0.068	0.227	0.300
Mg	0.000	0.000	0.000	0.000	0.000	0.061	0.414	0.391	0.000	0.000	0.000	0.000
Fe	1.800	1.811	1.792	1.779	1.828	1.824	1.472	1.489	1.776	1.776	1.772	1.772
Mn	0.055	0.045	0.049	0.041	0.045	0.029	0.041	0.045	0.070	0.066	0.045	0.054
Ca	0.101	0.079	0.107	0.098	0.070	0.083	0.069	0.078	0.100	0.103	0.103	0.091
Na	0.044	0.065	0.052	0.082	0.057	0.003	0.004	0.000	0.054	0.000	0.080	0.083
Na	0.306	0.288	0.213	0.155	0.050	0.138	0.008	0.061	0.154	0.165	0.168	0.149
Total	15.306	15.288	15.213	15.155	15.050	15.138	15.183	15.064	15.154	15.110	15.168	15.149

Fe⁺³ calculated by charge balance.

Table 4. Plagioclase Rim Compositions

Sample	Amphibolite					Pelite	
	L-47	L-112-N	L-75	Ga-3	L-100	L-77	L-36
SiO ₂	56.70	44.55	50.90	55.80	44.81	59.80	45.10
Al ₂ O ₃	27.70	35.27	31.60	28.20	35.34	25.70	36.00
CaO	9.01	19.27	13.60	9.20	17.91	7.07	17.80
Na ₂ O	6.45	0.63	3.80	6.40	1.14	7.69	1.18
K ₂ O	0.07	0.01	0.03	0.06	----	0.13	0.00
FeO	0.08	0.02	0.08	0.02	----	0.09	0.05
Total	100.01	99.75	100.01	99.68	99.20	100.48	100.13
Wt.% oxide normalized to 8(O)							
Si	2.542	2.063	2.312	2.513	2.080	2.653	2.068
Al	1.461	1.925	1.694	1.497	1.930	1.344	1.950
Ca	0.560	0.956	0.661	0.444	0.890	0.336	0.877
Na	0.433	0.056	0.334	0.559	0.102	0.662	0.104
K	0.002	0.000	0.001	0.002	-----	0.006	0.000
Fe	0.002	0.000	0.002	0.000	-----	0.002	0.001
Total	5.000	5.000	5.004	5.015	5.002	5.003	5.000
An	56	94	66	44	90	33	89

and orthoamphiboles (Figure 5a). Plagioclase of composition An₈₈₋₉₇ is confined to low variance assemblages containing phases such as staurolite, kyanite, or gedrite. Figure 5b is a plot of A-site Na in hornblende and X_{An} in coexisting plagioclase. Although there is a paucity of data there seems to be a break in plagioclase compositions between An₇₀ and An₈₈ over a continuum of Fe:Mg ratios and A-site Na of hornblende (see Spear, 1981, for a detailed study of naturally occurring plagioclase compositions in amphibolites).

Kyanite is present in three Laurel Creek amphibolite samples, as well as several pelitic and quartzo-feldspathic samples. Two samples (L-75 and L-112-N) contain euhedral grains in apparent textural equilibrium and exhibit distinct, sharp, angular to subangular grain boundaries (Figures 6a and c). Kyanite is evenly distributed in both samples. Sample L-100 contains one small grain of kyanite (0.1mm in diameter) that is almost entirely enclosed by hornblende. The grain is also in contact with anorthite (An₉₀). Given the included habit of the crystal and its singular occurrence, it is interpreted as either a relic of prograde metamorphism or as part of a localized equilibrium.

Staurolite is present in several samples from the Laurel Creek amphibolite, as well as in some of the pelitic and quartzo-feldspathic lithologies, and in one amphibolite of the Tallulah Falls Formation as an inclusion in a garnet (compositions are reported in Table 5). It occurs in a range of textures and assemblages (Table 1 and Figures 6a and b), and is present in several samples as inclusions only. Compositions reported here deviate significantly from the ideal composition,

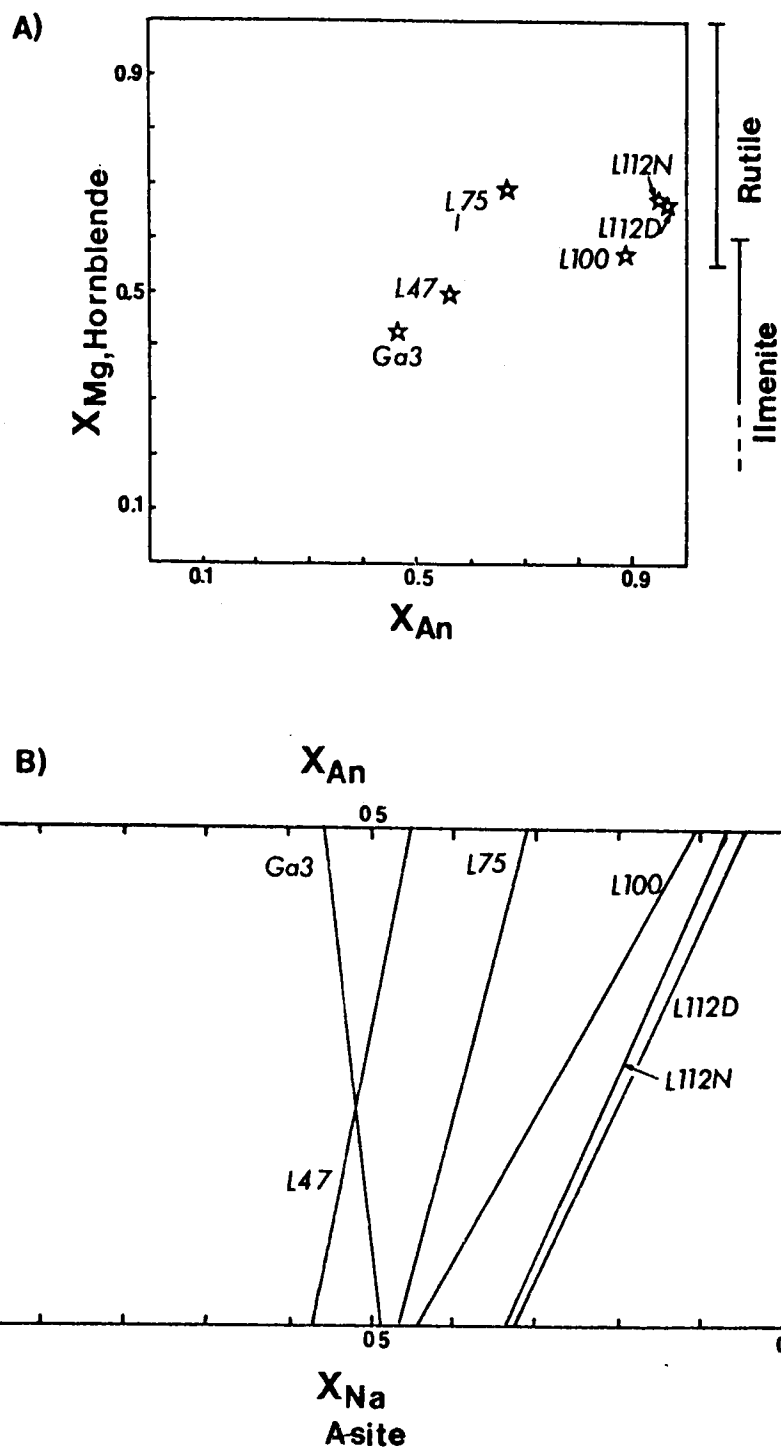


Figure 5. Plot of plagioclase compositions. (A) Plagioclase composition becomes more anorthitic as Mg:Fe increases in the bulk rock composition. Note the gap in plagioclase compositions over a continuum of Mg:Fe. As Mg:Fe decreases ilmenite is stabilized relative to rutile. (B) Measured amounts of Na in A-site of hornblende relative to the mole fraction of Na in coexisting plagioclase in Laurel Creek amphibolite.

Figure 6. Photomicrographs of Laurel Creek amphibolite assemblages in plane polarized light. (A) Photomicrograph of sample L-112-N,b; assemblage hornblende + gedrite + staurolite + kyanite + chlorite. (B) Sample L-112-L containing the assemblage hornblende + staurolite + gedrite. Scale as in (A). (C) Sample L-75 containing the assemblage hornblende + kyanite. Scale as in (A). (D) Coarse grained anthophyllite with hornblende intergrowths, sample L-88.

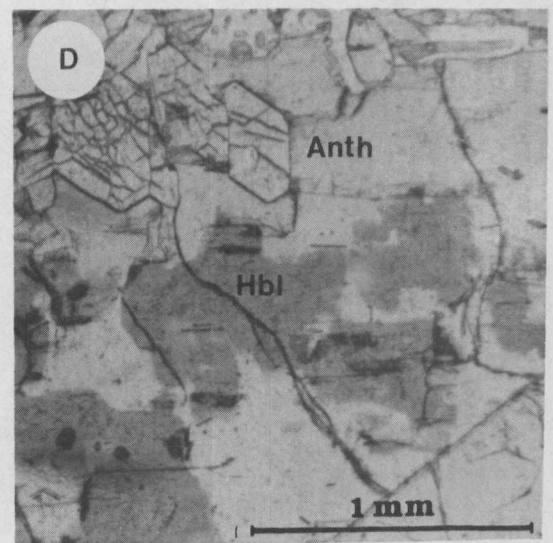
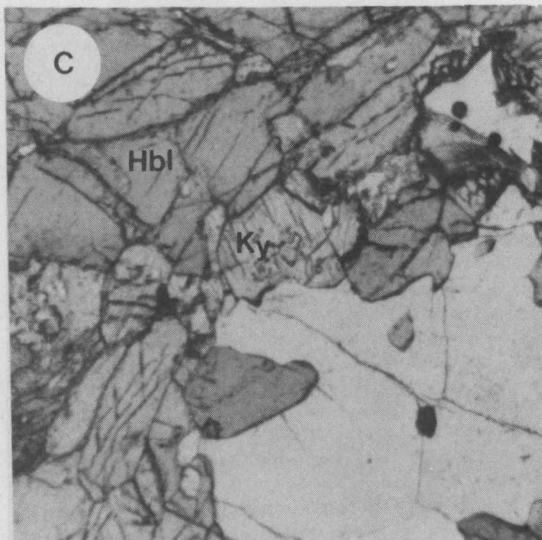
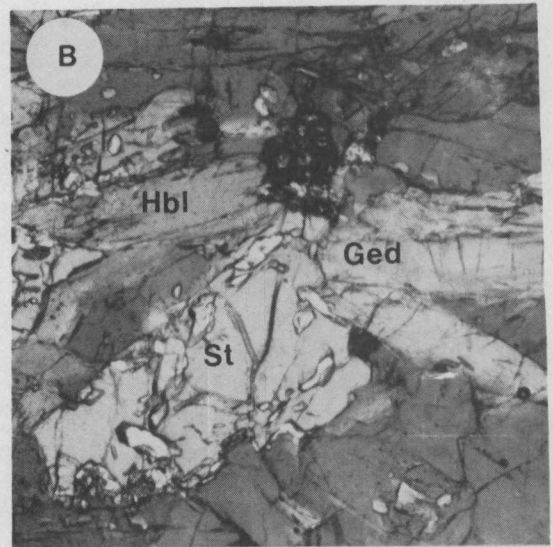
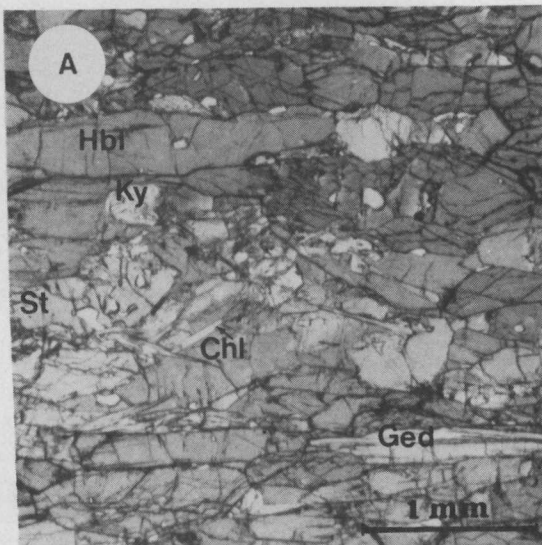


Figure 6

Table 5. Staurolite Compositions from Laurel Creek Amphibolite and Adjacent Pelitic Lithologies

Sample	Amphibolite					Pelite	
	L-79	L-34	L-100	L-100*	L-112-D	L-36	L-63A
SiO ₂	28.20	28.90	28.40	28.00	27.60	28.30	26.50
TiO ₂	0.67	0.65	0.46	0.75	0.54	0.68	0.24
Al ₂ O ₃	52.20	54.40	53.80	52.20	53.76	52.90	54.40
Cr ₂ O ₃	0.17	0.22	n.a.	n.a.	0.29	0.06	n.a.
FeO	12.40	11.60	12.80	12.20	11.70	13.90	13.60
MgO	3.42	2.47	3.48	4.39	4.12	2.82	2.25
MnO	0.14	0.19	n.a.	n.a.	0.22	0.12	0.11
ZnO	0.00	0.44	n.a.	n.a.	0.28	0.14	0.43
Total	97.2	98.87	98.94	97.54	98.51	98.92	97.53

Wt. % oxide normalized to 23(O)

Si	3.886	3.926	3.875	3.868	3.786	3.889	3.703
Ti	0.068	0.063	0.044	0.077	0.052	0.070	0.025
Al	8.650	8.719	8.655	8.515	8.687	8.569	8.966
Cr	0.008	0.020	n.a.	n.a.	0.028	.000	n.a.
Fe	1.365	1.320	1.454	1.412	1.324	1.590	1.584
Mg	0.696	0.499	0.705	0.905	0.833	0.567	0.468
Mn	0.016	0.020	n.a.	n.a.	0.028	0.010	0.012
Zn	0.000	0.043	n.a.	n.a.	0.028	0.010	0.024
X _{Mg}	0.34	0.27	0.33	0.39	0.39	0.26	0.23
Total	14.689	14.610	14.733	14.777	14.766	14.705	14.782

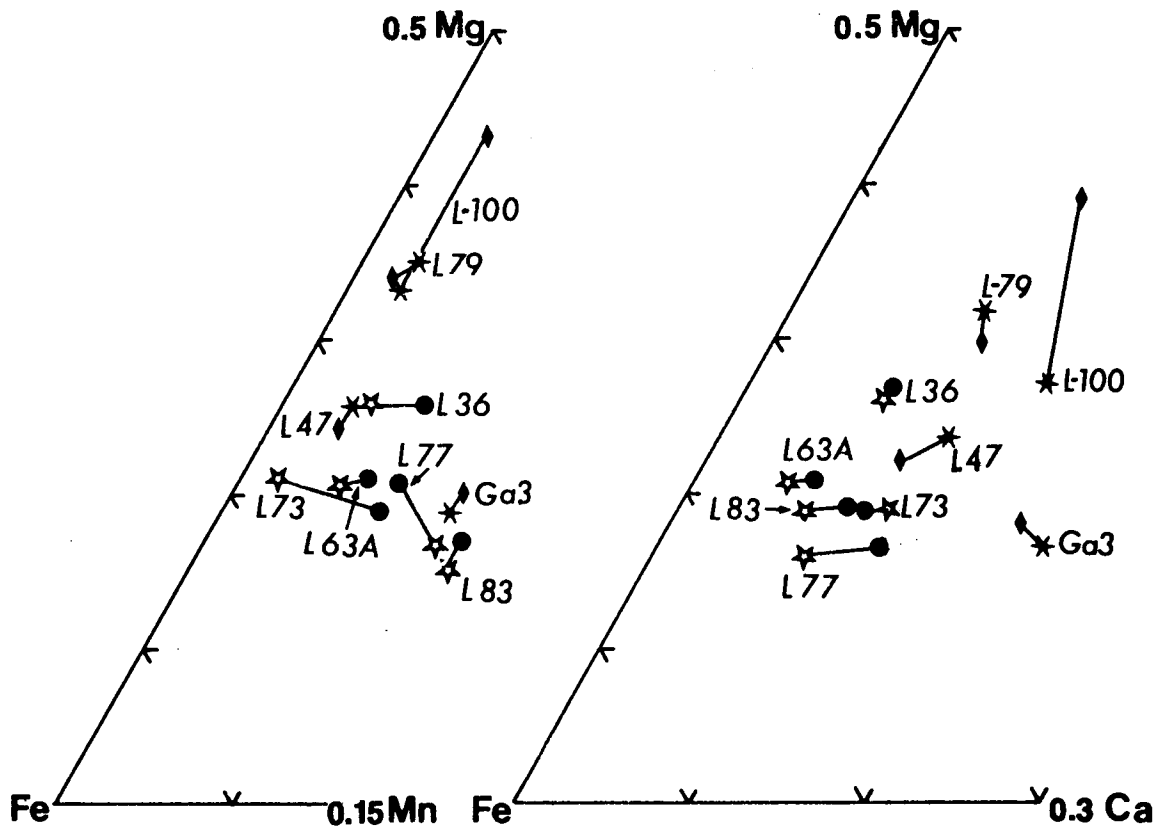
*Inclusion in garnet.

n.a. = not analyzed.

$\text{Fe}_{<2}\text{Al}_9\text{Si}_4\text{O}_{22}(\text{OH})_2$ (suggested by Smith, 1968); however, compositions are within the limits suggested by Griffin et al. (1982). The composition of staurolite varies greatly with bulk composition. X_{mg} ($\text{Mg}/(\text{Mg}+\text{Fe})$) ranges from 0.23 to 0.40. The minimum X_{Mg} value of 0.23 was found in a pelitic sample, whereas the maximum value, 0.40, was found as a rim composition in amphibolite sample L-112-N. Staurolite grains are fairly homogeneous; however, included grains of staurolite are more Mg-rich than matrix grains. Ti, the only significant minor element in these staurolites, tends to be enriched in cores.

Garnet compositions are presented graphically in Figure 7; core and rim values are presented in Table 6. Garnets in pelitic and quartzofeldspathic samples of the Tallulah Falls Formation are subhedral to euhedral, typically attaining a diameter no greater than approximately 1.5 mm. Garnets in the Tallulah Falls amphibolite are subhedral to euhedral and are never any larger than approximately 2 mm. In both lithologies the crystals appear to be postdeformational. Garnets from the Laurel Creek amphibolite are anhedral to euhedral and range in size 1 mm to 2 cm in diameter. Crystals are generally flattened and exhibit some rotation of inclusion trails relative to present foliation; however, many garnets appear to be completely postdeformational.

Zonation patterns illustrated in Figure 7 are somewhat erratic. Garnets from amphibolites are fairly homogeneous with respect to Mn, and exhibit slight enrichment in Ca at the cores. In one sample (L-100) there is a strong enrichment of Mg toward the rim. There is no preferred enrichment pattern, however, with respect to Fe and Mg in garnets



Garnet compositions

- | | |
|--------|---------------|
| * core |] amphibolite |
| ♦ rim | |
| ● core |] pelite |
| * rim | |

Figure 7. Garnet rim and core compositions from pelitic and amphibolitic lithologies. Tie lines connect rim and core compositions for the same sample.

Table 6. Garnet Compositions from Amphibolites and Pelites

Sample	Amphibolite						Pelite					
	L-112-D		L-100		L-79		L-47		L-77		L-36	
	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core
SiO ₂	39.20	39.40	38.80	38.60	38.30	36.60	38.30	36.90	36.90	36.60	38.20	37.60
Al ₂ O ₃	22.40	21.90	22.90	22.50	22.10	22.00	22.10	21.50	21.40	22.20	22.10	22.00
MgO	8.48	9.11	8.10	7.65	5.66	5.95	5.66	4.02	5.04	6.19	6.16	4.87
FeO	26.20	25.30	26.20	26.20	28.90	28.20	28.90	30.20	30.10	29.10	29.10	31.00
MnO	1.71	1.42	1.07	1.16	1.36	1.55	1.36	5.18	4.03	1.95	1.95	3.42
CaO	3.27	3.66	4.03	4.98	4.55	4.84	4.55	2.60	2.77	3.46	3.46	2.31
Total	101.26	100.79	101.10	101.09	100.87	99.14	100.87	100.40	100.24	101.02	100.97	99.46
Cations normalized to 12(O)												
Si	2.988	3.001	2.959	2.975	2.987	2.978	2.978	2.947	2.938	2.967	2.935	2.936
Al	2.008	1.969	2.053	2.033	2.032	2.022	2.022	2.017	2.005	2.042	2.050	2.052
Mg	0.961	1.032	0.919	0.872	0.962	0.654	0.654	0.478	0.598	0.714	0.720	0.603
Fe	1.668	1.609	1.677	1.676	1.66	1.876	1.876	2.015	2.005	1.894	1.909	2.048
Mn	0.109	0.091	0.067	0.074	0.084	0.089	0.089	0.349	0.271	0.127	0.126	0.227
Ca	0.266	0.237	0.329	0.409	0.263	0.378	0.378	0.222	0.233	0.287	0.300	0.194
Total	8.000	7.999	8.004	8.039	7.988	7.997	7.997	8.028	8.050	8.015	8.032	8.028

Cr and Ti not analyzed.

from amphibolite samples. Pelitic samples also exhibit reversals in Fe-Mg zonation, and generally show very little change in either component. Pelitic garnets are moderately zoned with respect to Ca and Mn; however, enrichment is not always in the same direction.

Chlorite is present in both prograde and retrograde assemblages. The two are easily distinguished from one another on the basis of texture and element partitioning. Retrograde chlorite occurs in isolated patches or bands in which crystals are arranged in small randomly oriented blocks. These bands or patches are in discord with major textures, such as foliation. Epidote, and less commonly tremolite, are associated with retrograde chlorite. Prograde chlorite has a fine bladed habit that is in textural harmony with adjacent crystals. The prograde nature of these grains was verified by regularity in element partitioning between coexisting phases. Chlorite has Mg-rich compositions, with an average $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio of 0.80. Compositions generally lie along the line representing the exchange ${}^{\text{vi}}\text{Al}^{\text{iv}}\text{Al} = {}^{\text{vi}}\text{Mg}^{\text{iv}}\text{Si}$ approximately 0.30 units from ideal clinochlore ($\text{Mg}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_2$). Figure 8 (compositions are presented in Table 7) indicates an approach to a 1:1 ratio between ${}^{\text{iv}}\text{Al}$ and ${}^{\text{vi}}\text{Al}$.

All amphibolite assemblages contain a Ti-saturating phase such as rutile, ilmenite, or sphene. Rutile occurs in Mg-rich samples, whereas ilmenite is stabilized in Fe-rich samples (ilmenite composition L-100 is presented in Table A-2 in the Appendix). This relationship was predicted by Thompson (1972) and has been observed by Spear (1982). The relationship is illustrated in Figure 5a, where the ratio $\text{Mg}:(\text{Mg}+\text{Fe})$ is

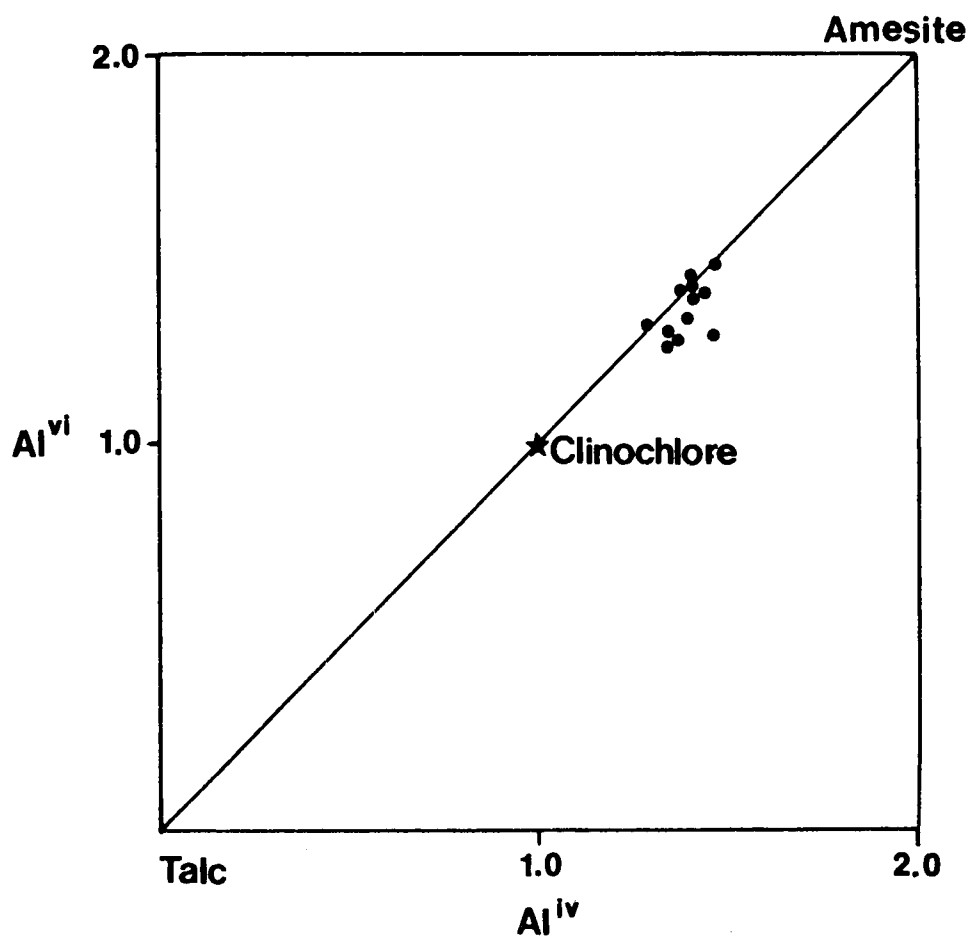


Figure 8. Chlorite compositions plotted in terms of molecular units of tetrahedral aluminum relative to molecular units of octahedral aluminum.

Table 7. Chlorite Compositions

Sample	L-112-D	L-100	L-99	L-75	L-112-N	L-34	L-79
SiO ₂	25.90	26.70	27.00	27.50	27.00	26.50	25.40
TiO ₂	0.07	0.14	0.08	0.07	0.12	0.09	0.07
Al ₂ O ₃	23.80	22.10	21.70	22.20	22.00	23.00	23.20
MgO	23.00	22.60	25.00	24.40	25.40	24.80	25.10
FeO	14.30	14.90	12.50	12.60	11.40	12.20	13.00
Total	87.07	86.44	86.28	86.77	85.92	86.59	86.77

Wt.% oxide normalized to 14(O)

Si	2.586	2.692	2.696	2.725	2.691	2.632	2.536
Ti	0.011	0.021	0.012	0.010	0.018	0.013	0.011
Al	2.801	2.627	2.555	2.594	2.585	2.693	2.731
Mg	3.422	3.396	3.720	3.604	3.773	3.671	3.735
Fe	1.194	1.257	1.044	1.044	0.950	1.013	1.086
Total	10.014	9.994	10.027	9.978	10.017	10.022	10.098

plotted against the anorthite content of coexisting plagioclase. Because modal hornblende is large, changes in its composition should monitor changes in bulk rock composition. Sphene is apparently stabilized in rocks with higher $\text{Ca}/(\text{Fe} + \text{Mg})$ ratios. This relationship is implied by its typical coexistence with prograde epidote and the fact that it never coexists with orthoamphibole or other aluminous phases lacking calcium, such as staurolite and kyanite.

Fe-Mg Enrichment

In Laurel Creek lithologies Fe/Mg enrichment follows the order staurolite >(?) garnet > gedrite > hornblende > chlorite > anthophyllite > talc. In Figure 9 the Mg/Fe ratio in staurolite is plotted against the Mg/Fe ratio in coexisting garnet. The K_D^{Fe} between staurolite and garnet in samples L-36, L-100, and L-79, is in reverse of that observed in several natural assemblages where the Fe/Mg ratio is greater in garnet than in staurolite (Ganguly, 1972; Thompson, 1977). Sample L-63A, the most iron rich pair, exhibits normal partitioning. Reversals in partitioning may represent substantial deviation from ideality (Thompson, 1957, Thompson, 1977), resulting from the ordering of Mg and Fe to energetically unique sites. There is some empirical evidence presented by Griffin and Ribbe (1973) which suggests that Mg is ordered to an octahedral site, whereas Fe is ordered to a tetrahedral site. However, these authors note that Schreyer (1968) synthesized a pure Mg-staurolite. Therefore, Mg must enter the Fe-tetrahedral position to a large extent. The measured differences in X_{Fe} values are very small,

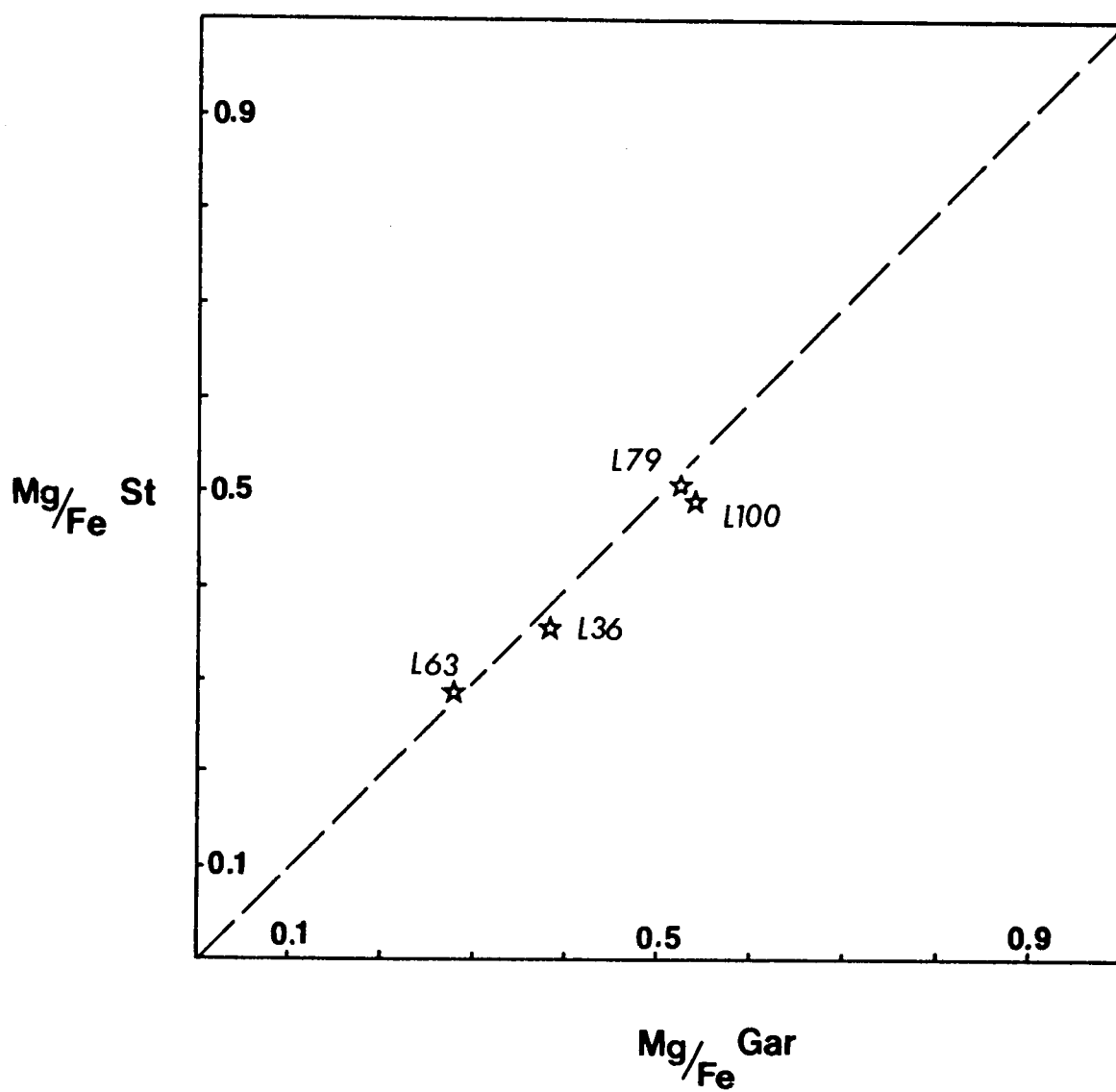


Figure 9. Mg/Fe staurolite is plotted against Mg/Fe garnet. Garnets in samples L-36, L-79, and L-100 are richer in Mg than coexisting staurolite.

and the K_D^{Fe} of natural garnet-staurolite pairs is close to unity (Ganguly, 1972). Consequently, this apparent reversal may be due to analytical error. It is noted, however, that very little data exists for such Mg-rich garnet-staurolite pairs. A Mg-rich pair reported by Ward (1984) also exhibits a reversal in Fe-Mg partitioning. Chlorite was observed to have a lower Fe:Mg ratio than coexisting anthophyllite, this is contrary to that reported elsewhere (Spear, 1982); therefore, chlorite may be retrograde.

CHAPTER 3

CHEMOGRAPHIC ANALYSIS OF THE LAUREL CREEK AMPHIBOLITE
AND ITS RELATIONSHIP TO THE COMMON AMPHIBOLITE
ASSEMBLAGE AND LOW-CA AMPHIBOLITES

Introduction

Chemographic analysis of the Laurel Creek amphibolite allows a fairly complete view of an amphibolite facies type, and indicates an approach to equilibrium. The presence of extra phases and crossing tie lines suggests that some assemblages buffered the chemical potential of H_2O . It is demonstrated chemographically and by algebraic means that the presence of hornblende + staurolite (and/or kyanite), hornblende + staurolite (or kyanite) + gedrite, hornblende + anorthite, or gedrite + anorthite is related to the common amphibolite assemblage by reaction relation. The presence of hornblende + staurolite + kyanite has been attributed to relatively high pressure metamorphism at moderate temperatures; however, assemblages similar to those found at Laurel Creek have been attributed to unusual bulk composition. Bulk compositions of low-variance assemblages are more mafic than an average basalt; however, they fall within the phase volume defined by the common amphibolite assemblage hornblende + chlorite + plagioclase + epidote, further indicating that Laurel Creek assemblages resulted from the breakdown of the common amphibolite assemblage. The petrogenetic grid of Spear (1977), developed for orthoamphibole-bearing assemblages, indicates that Laurel Creek assemblages equilibrated at relatively high pressures.

Phase Relations in the System
 $\text{FeO-MgO-Al}_2\text{O}_3\text{-CaO-Na}_2\text{O-SiO}_2\text{-TiO}_2\text{-H}_2\text{O}$

As a very good approximation, Laurel Creek amphibolites are composed of FeO, MgO, MnO, Al_2O_3 , Fe_2O_3 , CaO, Na_2O , K_2O , SiO_2 , TiO_2 , and H_2O . In order to reduce this system to a manageable number of components for chemographic analysis, several assumptions are made. MnO and K_2O are excluded either as trace elements or, in the case of K_2O , as stabilizing only one phase, such as biotite. TiO_2 may be projected from because rutile is almost always the Ti-saturating phase in low-variance assemblages. Water is considered as a boundary value component (Zen, 1967). There is no evidence for the presence of significant amounts of CO_2 , as might be indicated by carbonate phases. Because of the inability to distinguish between iron of different valence states from microprobe analyses, ferric iron content is a problem. It is here combined with Al; whatever quantity is present results in some unknown error in the Al composition of all phases considered. The absence of both hematite and magnetite in most low variance samples indicates a low oxidation state. Quartz is present in all samples observed; therefore, SiO_2 is considered to be in excess. The resulting simplified system is $\text{FeO-MgO-CaO-Na}_2\text{O-Al}_2\text{O}_3$ (for original arguments see Thompson, 1957; Hart and Graham, 1975; Laird, 1980; Spear, 1982).

The subsystem $\text{FeO-MgO-CaO-Na}_2\text{O-Al}_2\text{O}_3$ must be reduced to four components for a three dimensional chemographic analysis. Ideally reduction of a 3+n or 4+n component system is accomplished by projection from ubiquitous phases of fixed chemical composition, or from phases having

equivalent chemical potential for all assemblages considered (Thompson, 1957; Greenwood, 1975). The only phase, other than quartz, common to all assemblages is hornblende. The chemical variations in hornblende noted in Chapter 2 prohibit its use as a projection point in all assemblages.

Low variance amphibolite assemblages are here divided into an anorthite-present and an anorthite-absent group. The former group is chemographically treated by projection through anorthite (An94), the latter group by projection through hornblende. These subdivisions and their respective projections are of utility in demonstrating that the assemblages investigated approach equilibrium and in comparing phase relationships to other amphibolite assemblages.

Figure 10a is a projection of the anorthite-present assemblages. These phases are projected through an average anorthite (An94) into the tetrahedron Fe-Mg-Al-Na_{0.1}. (Unless otherwise noted all projections are in terms of molecular proportions.) The actual measured range in anorthite composition is An90 to An97. Phase volumes generally separate indicating an approach to equilibrium; however, sample L-112-D and L-100 exhibit crossing tie-lines. These crossing tie-lines suggest that either $\mu\text{H}_2\text{O}$ or $\mu\text{anorthite}$ is not equivalent in all assemblages considered. Despite the crossing tie-line relationship between these two assemblages, the assemblages presented should represent a facies type for this grade of metamorphism.

The general separation of phase volumes is consistent with the idea that proper assumptions were made in choice of prograde assemblages.

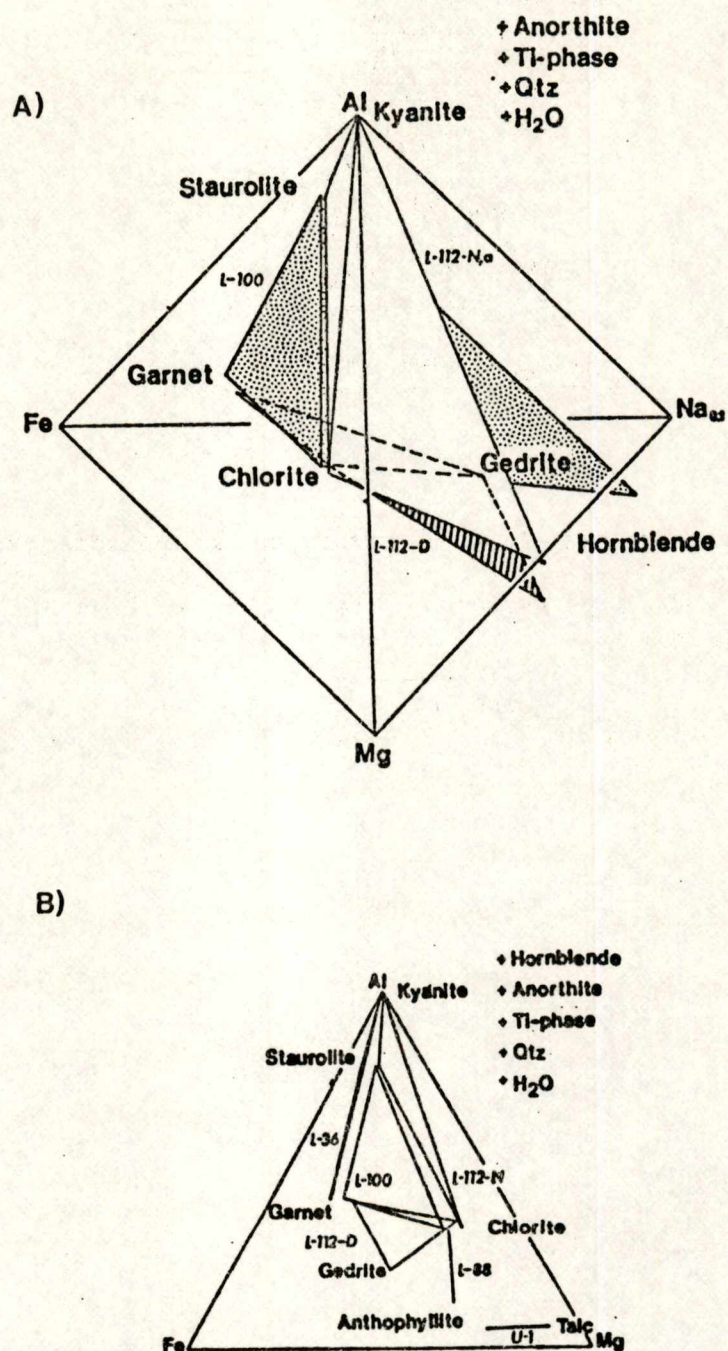


Figure 10. Projections of anorthite present assemblages. (A) Laurel Creek assemblages projected through the anorthite composition An₉₄ into the tetrahedron Fe-Mg-Al-Na_{0.1}. Si and Ti are considered to be in excess. The chemical potential of H₂O is considered as a boundary value component. (B) Laurel Creek assemblages are projected onto the Fe-Mg-Al plane through anorthite (An₉₄) and hornblende.

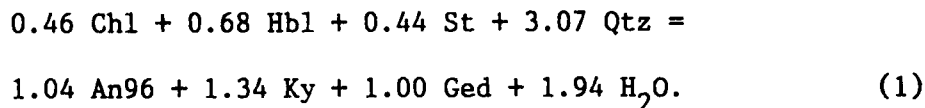
Sample L-100 also contained a small crystal of kyanite partially enclosed by a crystal of hornblende. The kyanite is also in contact with anorthite. The hornblende crystal containing kyanite is 25% more aluminous than other grains analyzed in that particular thin section. The highest aluminum value was found several tens of microns from the kyanite grain, indicating that the high aluminum counts were not the result of an edge effect. It is suggested that the kyanite is either the result of a local equilibrium or that it is a relict of prograde metamorphic reactions. Sample L-112-D contains several crystals of staurolite included in hornblende, garnet, and anorthite. One crystal of staurolite is in contact with both anorthite and hornblende. However, it is almost entirely enclosed in anorthite. Staurolite in this sample is interpreted as being a relict of prograde metamorphic reactions. The nature of the staurolite-out and the kyanite-out reactions is unclear due to the absence of other phases occurring as inclusions.

Sample L-112-N considered in the entirety of the thin section contains the following phases:

Hornblende + Gedrite + Anorthite + Kyanite + Staurolite
+ Chlorite + Quartz + Rutile.

Gedrite and anorthite, however, are never in contact; therefore, the thin section is divided into an anorthite-absent and an anorthite-present assemblage. This relationship seems to be recurrent at Laurel Creek; when plagioclase is absent, an orthoamphibole is always present

as the other Na-Ca phase. Alternatively this sample may have buffered $\mu\text{H}_2\text{O}$ by the reaction:



This reaction was balanced using measured compositions for assemblage L-112-N. Compositions are reported in Chapter 2. Spear (1982) observed that the carbonate-absent set of amphibolites in the Post Pond Volcanics (mineralogically similar to those observed at Laurel Creek) commonly contained one more phase than would be expected in a system in which $\mu\text{H}_2\text{O}$ was externally controlled.

Figure 10b is a projection from anorthite (An₉₄), hornblende (sample L-79) and quartz; the chemical potential of H_2O is considered to be equivalent in all assemblages. This is essentially the projection employed by Spear (1982). Spear (1982) projects from andesine; however, this difference has no effect on the AFM relations. Because all phases are very close to the AFM plane variations in the composition of hornblende also have little effect on phase relations.

Figure 11a is a projection of the anorthite-absent assemblages. These phases are projected through the composition of hornblende L-79 into the tetrahedron Fe-Mg-Al-Na_{0.05}. There is little difference in the hornblende composition of these two assemblages. Separation of phase volumes along parallel planes, suggests equilibrium was approached. All low variance assemblages in both assemblage sets contain at least two Na-Ca phases. These rocks differ from the anorthite-present assemblages

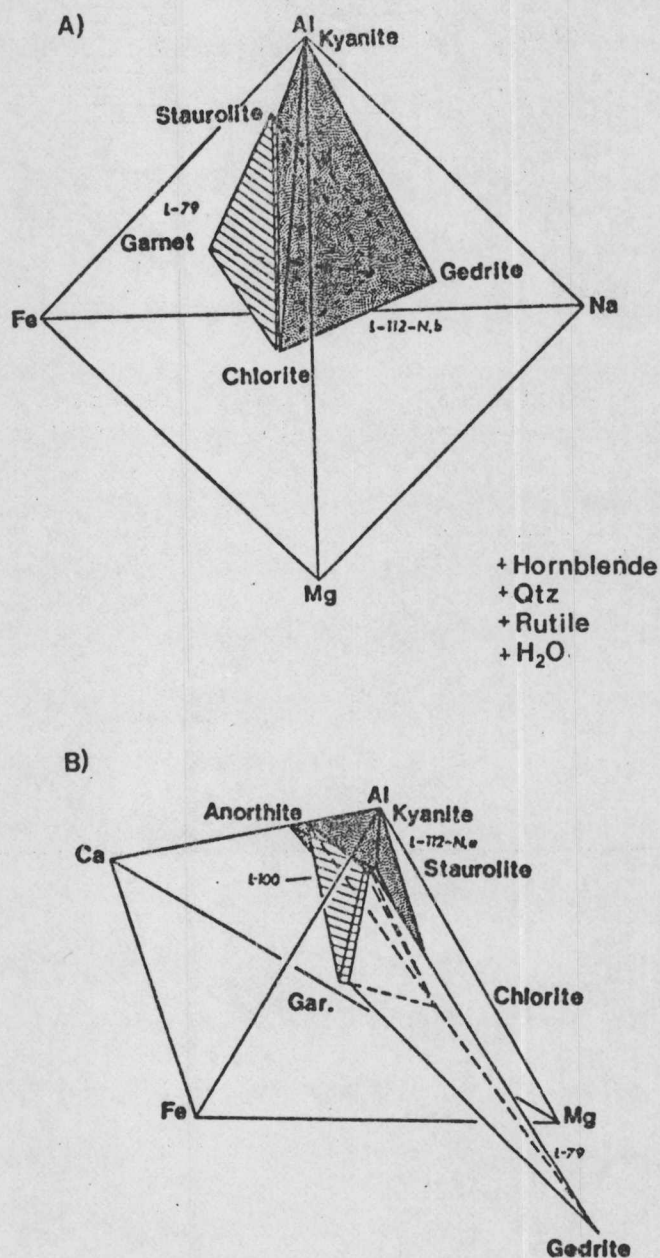


Figure 11. Anorthite-absent projections. (A) This is a projection of the anorthite (plagioclase)-absent assemblages through the composition of hornblende L-79 into the tetrahedron Fe-Mg-Al-Na_{0.05}. (B) This is a projection of both the anorthite present and anorthite-absent assemblages through the composition of hornblende L-79 into the tetrahedron Fe-Mg-Al-Ca. In both projection Si and Ti are considered as excess components; H₂O is considered as a boundary value component.

only in their bulk Na:Ca ratio. Those assemblages containing hornblende and anorthite would have a lower bulk Na:Ca ratio than assemblages containing hornblende and gedrite. The rationale behind this assumption is that gedrite, which substitutes for anorthite, has a considerably greater Na:Ca ratio. This relationship can be visualized in Figure 11b; here assemblages are projected through the composition of hornblende L-79 into the tetrahedron Fe-Mg-Al-Ca. Projection through hornblende gives gedrite a negative Ca value, thereby allowing a lower Ca set of assemblages, composed of the same AFM minerals. Therefore, gedrite may coexist with either staurolite or kyanite at the same grade chlorite and garnet are stable as long as plagioclase is absent (see Figure 10b).

High-variance "normal" assemblages that are most common at Laurel Creek, such as hornblende + plagioclase + garnet + quartz + ilmenite + rutile or hornblende + plagioclase + epidote + quartz + ilmenite + sphene, may in a nonrigorous manner be shown on these projections. Ignoring the significant differences between the hornblende compositions of these high-variance assemblages and hornblende composition L-79, it is noted that epidote plots just below anorthite in Figure 11b with tie lines extending to garnet, whereas plagioclase compositions much more sodic than An₈₈ plot at negative infinity.

Significance of Staurolite + Kyanite + Hornblende Stability

Although aluminous phases such as kyanite and staurolite typically occur in rocks of pelitic composition, they have also been reported in rocks of mafic composition (e.g., Gibson, 1978; Hellman and Green, 1979;

Ward, 1984; Selverstone et al., 1984). Selverstone et al. (1984) have made the important observation that the coexistence of hornblende with either kyanite or staurolite prohibits, by reaction relationship, the stability of the common amphibolite assemblage composed of calcic amphibole + plagioclase (An_0 - An_{50} in medium pressure terrains) + chlorite + epidote + garnet (defined and discussed in detail by Laird, 1980; Thompson et al., 1982, Robinson et al., 1982). This is the dominant divariant assemblage in the model system FeO - MgO - Al_2O_3 - CaO - Na_2O - SiO_2 - H_2O (where μH_2O is externally controlled and SiO_2 is in excess) in medium and low pressure metamorphic terrains. Selverstone et al. (1984) have, therefore, proposed that the kyanite + hornblende tie line reflects pressures higher than those appropriate to the stability of the common assemblage. This argument is based, in part, upon the observation that the assemblage hornblende + kyanite + staurolite is absent in terrains for which estimated pressures are less than 6 kbar but is present (see Cooper, 1980) in terrains suspected of being metamorphosed at higher pressures at moderate temperatures (550-700°C). Selverstone et al. (1984) calculated final pressures of equilibration to be 7-8 kbar, for the hornblende + kyanite + staurolite Gabbro of the Lower Schieferhülle Series, Austria.

Experimental work corroborates this hypothesis. Hellman and Green (1979) subjected rocks of basaltic composition, in a hydrous system, to pressures of 22-24 kbar and temperatures of 750°C. The resultant phases included high-Mg staurolite, kyanite, orthoamphibole, clinopyroxene, garnet, and glass. Significant is the general similarity of these

phases with those observed at Laurel Creek. Besides the dehydration of hornblende to form clinopyroxene, there would be no discontinuous reaction relationships between the two sets of assemblages.

It has been suggested that the presence of Mg-rich staurolite is an indication of higher pressure metamorphism (Ward, 1984). This idea was largely based on the preceding experimental results and those of Schreyer (1968) who synthesized a pure Mg endmember staurolite in the system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$. The minimum pressure of stability for this phase was estimated to be approximately 12 kbar at 750°C. At both higher and lower temperatures this phase is stable at higher pressures. Schreyer (1968) suggested that the absence of reported natural staurolites approaching the composition of the Mg-endmember may be due to the paucity of rocks of the appropriate composition subjected to high enough pressures. The maximum value of $\text{Mg}/(\text{Mg} + \text{Fe})$ found at Laurel Creek is 0.40. The maximum reported in natural assemblages is 0.56 (Ward, 1984), and the maximum resulting from the high-pressure experiments of Hellman and Green is 0.57. This may indicate relatively high pressures of metamorphism at Laurel Creek.

Reaction Relationship of the Common Amphibolite Assemblage to the Laurel Creek Assemblages

The reaction relationship between the common amphibolite assemblage and the assemblage staurolite-kyanite-hornblende was chemographically demonstrated in a "standard" amphibolite $\text{CaO-Na}_2\text{O-Al}_2\text{O}_3\text{-(FeO+MgO+MnO)}$ tetrahedron by Selverstone et al. (1984). Figure 12a is a similar projection with Laurel Creek assemblage L-75 plotted to demonstrate the

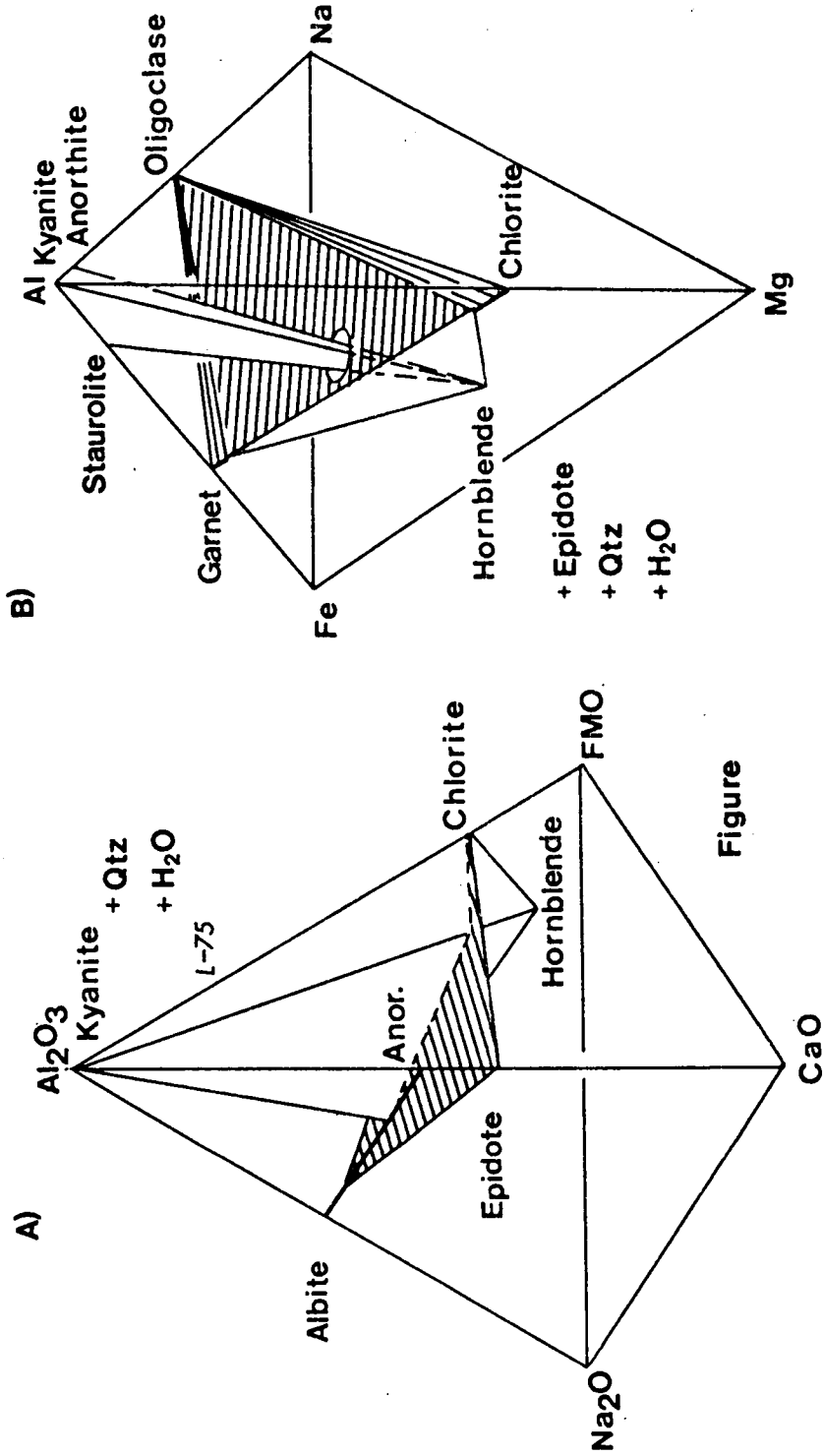


Figure 12. Reaction relationship of hornblende + kyanite + stauroite + anorthite assemblages viewed from standard amphibolite projections. (A) This projection combines Fe and Mg and assumes that Ti and Si are in excess. The chemical potential of H_2O is considered as a boundary value component. Assemblage L-75 is plotted to demonstrate the reaction relationship of this Laurel Creek assemblage to the common assemblage. (B) This figure is a projection of phases through the composition of epidote and quartz, enabling a view of Fe-Mg amphibolite space.

clear reaction relationship between kyanite + hornblende and the plane represented by the phases oligoclase + epidote + chlorite. In the sense of phase rule "legality," this projection does not allow both chlorite and garnet to coexist with hornblende + epidote + oligoclase. However, tie lines between garnet, chlorite, and hornblende are significant across Fe-Mg composition space in amphibolites of medium-pressure facies series metamorphism (Laird, 1980; Hart and Graham, 1975). Therefore, combining Fe and Mg obscures an often significant portion of amphibolite space. Figure 12b is a projection through epidote and quartz into the tetrahedron Fe-Mg-Na-Al, $\mu\text{H}_2\text{O}$ is considered to be a boundary value component. This diagram indicates that after tie lines are formed between hornblende and either kyanite, staurolite, or anorthite, the common assemblage chlorite + epidote + oligoclase + calcic amphibole may still persist for Mg-rich bulk compositions (Figure 12b). At Fe-rich bulk compositions the assemblage garnet + oligoclase + epidote + calcic amphibole is also permissible at the same grade at which hornblende coexists with kyanite or staurolite. However, the full divariant assemblage garnet + chlorite + epidote + oligoclase + hornblende is prohibited. "Normal" upper amphibolite facies assemblages, such as hornblende + andesine + garnet + epidote, are prevalent at Laurel Creek; however, the full common assemblage is not observed.

The epidote projection is useful for demonstrating reaction relationships across Fe-Mg space; however, the key assemblages observed at Laurel Creek do not contain epidote. Kyanite and staurolite were

reported to coexist with epidote in amphibolites of the Tauern Window, Austria (Selverstone et al., 1984).

Demonstration of the reaction relationship between the assemblages at Laurel Creek and the common assemblage is accomplished by a projection through chlorite (composition L-79) into the tetrahedron Fe-Na-Ca-Al. In Figures 13a-d four such projections are presented. Because equilibrium conditions have been indicated in a previous section, phase volumes are presented separately for clarity. In each diagram, tie lines crossing the common assemblage plane oligoclase + epidote + garnet are numerous, indicating that the two assemblages cannot coexist at equivalent physical conditions.

The composition of gedrite is such that it plots at a substantially negative aluminum value when projected through the composition of chlorite. For aesthetic purposes the aluminum value of gedrite has been substantially increased. This adjustment will not effect the reaction relationship between the gedrite + anorthite tie line and the plane oligoclase + epidote + garnet. It appears as though tie lines between gedrite and staurolite, or kyanite, cross the common assemblage tie plane; however, algebraic methods indicate that no reaction relationship exists unless hornblende is also present.

Graphical methods are not necessary to demonstrate the reaction relationship between the assemblages found at Laurel Creek and the common assemblage. Univariant reactions may be generated by linear programming. Reactions relating the the common assemblage to the assemblages at Laurel Creek are presented in Table 8. Compositions of

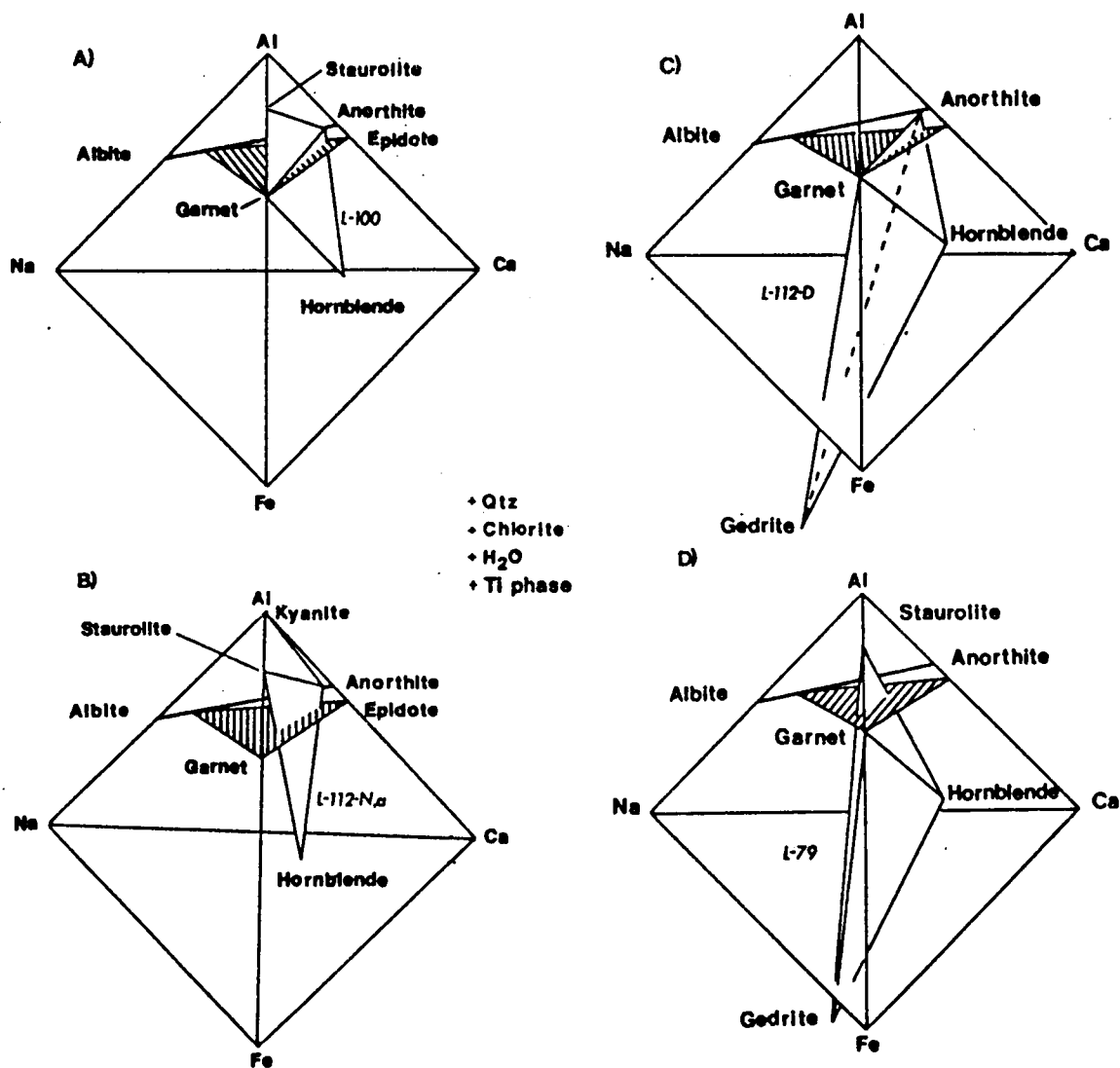


Figure 13. Laurel Creek assemblages projected through chlorite, quartz, and rutile into the tetrahedron Fe-Na-Ca-Al. The chemical potential of H₂O is assumed to be externally controlled. In A-D it is clear that Laurel Creek assemblages are in reaction relationship to the common assemblage.

Table 8. Reactions Relating the Common Amphibolite Assemblage to the Laurel Creek Amphibolite Assemblages

Common Amphibolite Assemblage = Laurel Creek Assemblages	
4.16 Epi + 1.00 Olg + 0.88 Chl + 0.49 Gar + 3.42 Qtz =	
6.87 An + 1.31 Hbl + 4.30 H ₂ O	(3)
1.65 Epi + 1.00 Olg + 1.55 Chl + 0.85 Gar + 3.16 Qtz =	
2.82 Ky + 2.29 Hbl + 4.72 H ₂ O	(4)
1.58 Epi + 1.00 Olg + 1.61 Chl + 1.34 Gar + 3.42 Qtz =	
0.76 St + 2.29 Hbl + 4.17 H ₂ O	(5)
4.40 Epi + 1.09 Olg + 1.56 Chl + 1.00 Gar + 8.15 Qtz =	
9.59 An + 1.73 Ged + 6.73 H ₂ O	(6)
1.00 Olg + 11.77 Chl + 7.45 Gar + 36.16 Qtz =	
11.14 Ky + 1.00 Hbl + 12.29 Gd + 33.77 H ₂ O	(7)
1.00 Olg + 8.88 Chl + 6.94 Gar + 22.60 Qtz =	
2.27 Str + 1.00 Hbl + 8.88 Ged + 23.35 H ₂ O	(8)
0.45 Olg + 7.55 Chl + 4.83 Gar + 28.73 Qtz =	
10.62 Ky + 1.00 An + 8.38 Ged + 21.88 H ₂ O	(9)
2.91 Olg + 4.51 Chl + 2.48 Gar + 1.00 Qtz + 4.79 Epi =	
8.21 Coru + 6.68 Hbl + 13.74 H ₂ O	(10)

minerals are taken from minerals analyzed in this study and listed in Table A-3 in the Appendix.

If two n-dimensional phase volumes overlap, they may not coexist at equivalent physical conditions (Greenwood, 1967; Braun and Stout, 1975). Such a relationship between two assemblage sets is commonly demonstrated by means of projections; however, these may be misleading. Braun and Stout (1975) presented the general conditions for overlap by the relationship:

$$\sum_{i=1}^M a_i A_i = \sum_{j=1}^K b_j B_j, \quad (2)$$

where A_i and B_j represent the measured compositions of the phases in the two assemblage sets, a_i and b_j are the stoichiometric coefficients (all a_i and b_j must have opposite signs), and $M + K = n + 1$ (i.e., the phase rule variance must be one). If any such reactions are generated between two sets of mineral assemblages, the two volumes must overlap. All of the reactions listed in Table 8 are of this form, where summation A is defined by the phases garnet, chlorite, epidote, and oligoclase, and the summation B is composed of the phases kyanite, staurolite, gedrite, and anorthite. All phase volumes depicted in Figure 13 can be derived by linear combinations of the reactions listed in Table 8.

Although hornblende is part of the common assemblage, it only participates in these reactions as a product. This is consistent with the high modal content of hornblende in the Laurel Creek amphibolites (approximately 80-90%). The low modal quantity of chlorite (<5%) is

consistent with its placement on the reactant side of these reactions. Garnet, however, may still be fairly abundant in low variance assemblages (20%).

The results of the preceding phase analysis of rocks from Laurel Creek are consistent with the conclusion of Selverstone et al. (1984), that the coexistence of hornblende with either kyanite or staurolite prohibits the stability of the common assemblage. Also recognized is the equivalent significance of assemblages containing gedrite + anorthite, hornblende + anorthite, hornblende + staurolite + gedrite and hornblende + kyanite + gedrite. Orthoamphibole-bearing amphibolites mineralogically similar to those observed in this study have been discussed within the context of low-Ca amphibolites (Robinson et al., 1982). Such rocks may be low in Ca; however, they are clearly in reaction relationship to the common amphibolite assemblage.

Reaction (10), listed in Table 8, is an interesting result of linear programming. If SiO_2 is treated as an understaurated component, the assemblage corundum + hornblende may be derived from the common assemblage. Although this assemblage was not noted in the study area, McElhaney and McSween (1984) noted the assemblage kyanite + corundum + anorthite + hornblende in a partially metamorphosed troctolite elsewhere in the Blue Ridge. This suggests that the hornblende + corundum tie line is of similar significance to the kyanite + hornblende tie line.

The Bulk Composition of Laurel Creek Amphibolite

In the previous section it was demonstrated that assemblages at Laurel Creek are in reaction relation to the common amphibolite assemblage. The presence of kyanite, staurolite, and gedrite in the Laurel Creek amphibolite is intuitively suggestive of an unusual bulk composition. Similar rocks from the Post Pond Volcanics have been discussed in the context of low-Ca amphibolites (Robinson et al., 1982). The assemblage hornblende + staurolite + garnet + chlorite + andesine from this same group of rocks has been attributed to an aluminous bulk composition (Spear, 1982; Selverstone et al., 1984). Bulk compositions of four Laurel Creek assemblages are presented in Table 9 (see Table 1, p. for a list of phases in these samples). Also presented in this table are normative calculations. Note that compositions are quartz to olivine normative but not corundum normative. Figure 14 is an AC(FM) diagram in which phases and bulk compositions are plotted in terms of molecular proportions. Also plotted is a field representing compositions of amphibolites from Vermont from which amphibolites with the common assemblage were sampled by Laird (1980) (mention, however, was made of the presence of amphibolites containing Fe-Mg amphibole) and a field representing low-Ca amphibolite compositions. The field representing low-Ca amphibolites is composed of seventeen samples reported by Tilley (1938) and Lal and Moorhouse (1967). All but three samples fall on the Al_2O_3 -FMQ join. These low-Ca amphibolites all lack hornblende, whereas Laurel Creek samples always contain high modal quantities of hornblende (≈ 65 -90%). Significantly, Laurel Creek compositions fall within the region defined by the phases hornblende + plagioclase +

Table 9. Bulk Rock Chemistry of Selected Laurel Creek Amphibolite Samples with Normative Calculations

Sample	L-112-D	L-112-N	L-100	L-79
Elements				
SiO ₂	48.76	47.75	44.43	47.27
TiO ₂	0.51	0.43	1.94	0.66
Al ₂ O ₃	13.41	15.62	16.54	13.81
MgO	13.42	12.41	9.28	12.54
FeO _F	12.12	10.67	14.56	12.57
MnO	0.23	0.22	0.26	0.23
CaO	8.99	9.57	9.37	9.42
Na ₂ O	1.35	1.53	1.64	1.55
K ₂ O	0.11	0.13	0.18	0.15
P ₂ O ₅	0.07	0.06	0.23	0.10
Total	98.97	98.39	98.43	98.30
C.P.I.W. normalization				
Qtz	0.88	0.45	--	--
Orth	--	0.06	0.31	0.24
Ab	3.83	4.83	7.17	7.16
An	33.20	39.41	41.98	34.82
Di	5.69	5.75	3.21	8.96
Wo	2.98	2.93	1.61	4.54
En	1.60	1.67	0.76	2.42
.Fs	1.20	1.15	0.84	2.00
Hp	54.98	48.23	28.72	30.88
En	31.63	28.65	13.74	16.97
Fs	23.35	19.58	14.98	13.90
Ol	--	--	14.37	16.56
Fo	--	--	6.53	8.71
Fa	--	--	7.84	7.76
Il	1.19	1.08	4.04	1.18

Fe assumed all Fe⁺².

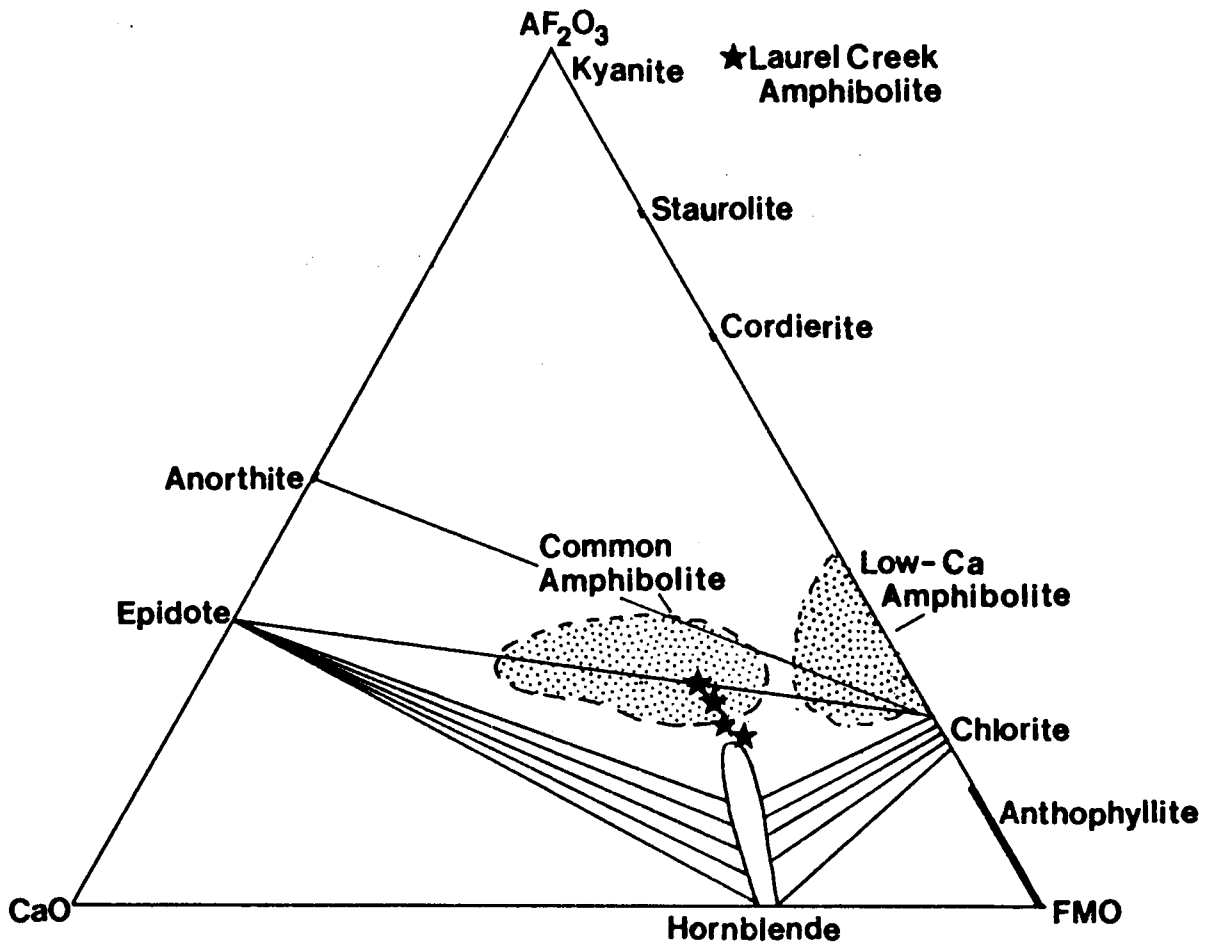


Figure 14. ACF diagram demonstrates general bulk compositional differences between various amphibolite types. The field in the center of the diagram marked "common amphibolite" is taken from Laird (1980); the region along the AF_2O_3 -FMO join represent low-Ca amphibolites taken from Lal and Moorhouse (1969) and Tilley (1935). Ferric iron for the Laurel Creek samples was calculated using an $\text{Fe}^{+2}/\text{Fe}^{+3}$ ratio common to amphibolites (McElhaney and McSween, 1984).

chlorite + epidote, further indicating that these assemblages are derived from the common assemblage. If an $\text{Fe}^{+3}/(\text{Fe}^{+2} + \text{Fe}^{+3})$ ratio of 0.71 is assumed (mean value calculated by McElhaney and McSween, 1984 from several wet chemical analysis of amphibolites) bulk compositions of amphibolites from Laurel Creek overlap the common amphibolite field.

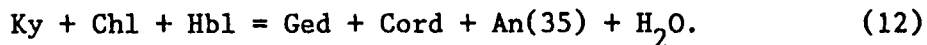
It has been demonstrated that Laurel Creek assemblages may be derived from the common assemblage, but it has not been demonstrated that their composition is common. The question must be asked whether such assemblages are rare only because of external physical conditions; or does an uncommon bulk composition have an effect? Kyanite, staurolite, gedrite, and anorthite, were absent in all but one sample of the Tallulah Falls amphibolite (out of approximately 40 samples petrographically observed). These phases were uncommon in the Laurel Creek complex (they are rare enough to have been completely missed in a previous study of the complex). The bulk composition of kyanite-staurolite amphibolites must therefore fall within a small compositional "window" which allows the reaction relationships listed in Table 8 to become manifest. This would be a situation analogous to that observed for the garnet granulite-eclogite transition in which the temperature and pressure of the transition is dependent on bulk composition (Green and Ringwood, 1972). Rocks falling outside of this compositional "window" would be composed of high variance combinations of the assemblages hornblende + epidote + plagioclase + chlorite and hornblende + epidote + plagioclase + garnet (see Figure 12b, p. 45). These are not unusual assemblages in the amphibolite facies. Therefore, conditions could be

appropriate for the development of hornblende + kyanite + staurolite + gedrite + anorthite in several terrains; however, due to bulk composition this assemblage does not occur. The above propositions are not meant to diminish the significance of the reaction relationship existing between Laurel Creek assemblages and the common amphibolite assemblage observed in medium pressure terrains. Based on empirical field and laboratory observation, this transition is related to high pressure metamorphism at temperatures of the amphibolite facies.

Comparison of Phase Relationships to Other Orthoamphibole-Bearing Amphibolites

The development of a petrogenetic grid based on naturally occurring assemblages is a major goal of metamorphic petrology; it is to this end that the following discussion is directed. Amphibolites typically adjust to changing physical conditions by continuous reactions; orthoamphibole-bearing amphibolites are an exception to this condition (Robinson et al., 1982). Spear (1977) developed a petrogenetic grid for assemblages similar to those observed at Laurel Creek (also see Robinson and Jaffe, 1969a). Reactions presented by Spear are inferred from chemographic relationships on a AFM diagram in which phases are projected through andesine and hornblende. Low-variance assemblages from Laurel Creek contain no plagioclase or plagioclase An₈₈₋₉₇. Reactions inferred from the AFM diagram of the andesine + hornblende and the anorthite + hornblende (Figure 10b, p. 38) projection presented in this study are not significantly different. Although Figure 10b indicates that garnet + chlorite is stable at Laurel Creek, the divariant field kyanite +

gedrite + staurolite is the stable assemblage and is bounded by the univariant reactions presented by Spear (1977):



These reactions bracket relatively high pressures on the petrogenetic grid. A portion of the petrogenetic grid of Spear (1977) is presented in Figure 15. The region marked "LC" represents the stable divariant field at Laurel Creek. The analogous reaction to (11), involving anorthite, has not occurred at Laurel Creek.

The lowest pressure and temperature region on the petrogenetic grid of Spear (1977) contains staurolite + hornblende and must be in reaction relation to the common assemblage.

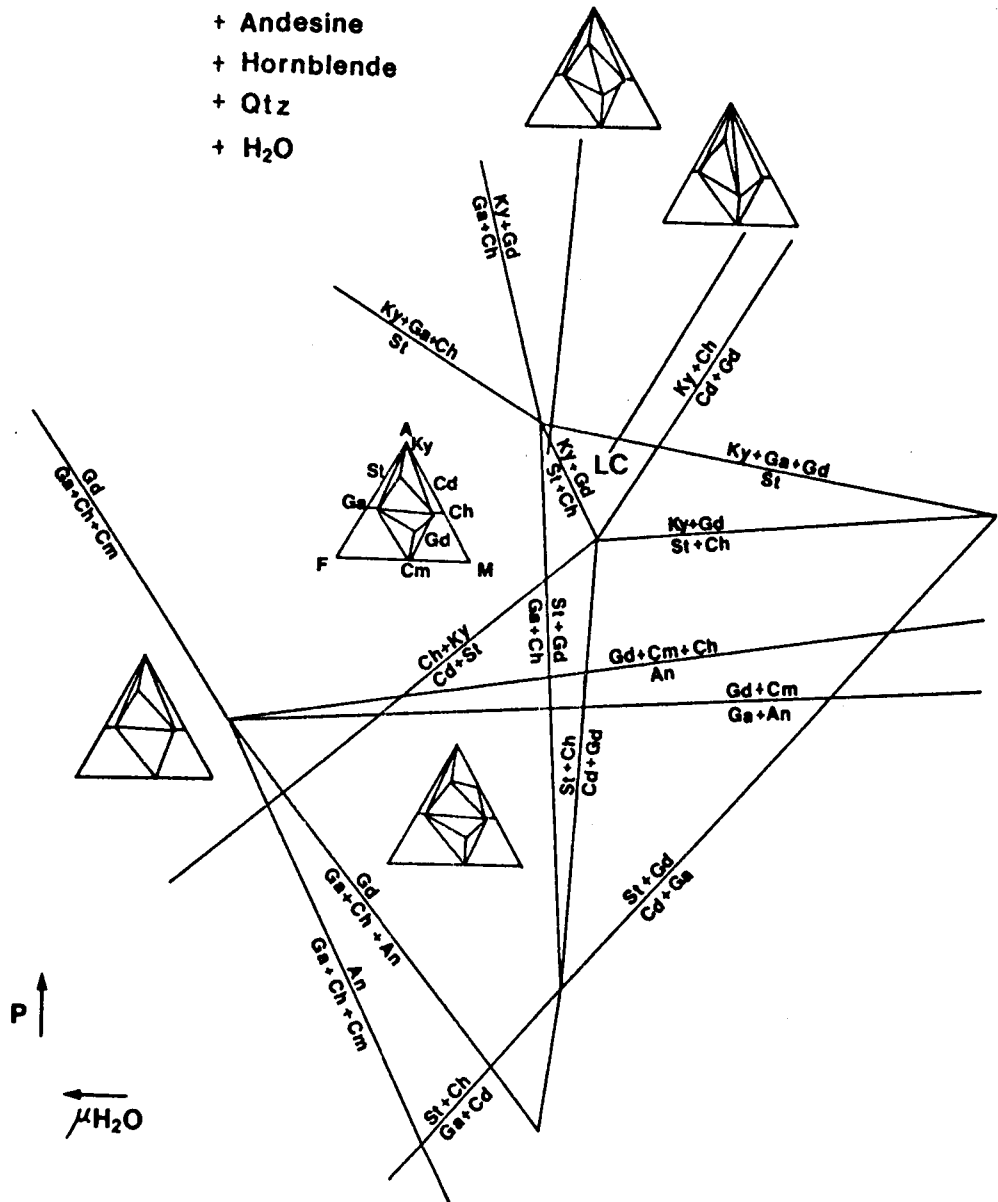


Figure 15. Petrogenetic grid for orthoamphibole amphibolites taken from Spear (1977). Conditions at Laurel Creek are bounded by the reactions enclosing the region marked LC. Abbreviations: Gd = gedrite, An = anthophyllite, Cd = cordierite, Ky = kyanite, St = staurolite, Ch = chlorite, Ga = garnet.

CHAPTER 4

GEOTHERMOMETRY AND GEOBAROMETRY

Pressure and Temperature Conditions Constrained
by Mineral Stabilities

Reactions presented in Figure 16 broadly constrain the pressure and temperature of peak metamorphism at Laurel Creek. Both the upper and lower temperatures are bracketed by the stability of staurolite + quartz. This stability field has a lower temperature range of ≈ 530 - 560°C and a maximum temperature of ≈ 675 - 700°C (Ganguly, 1972; Richardson, 1967). The P-T position of both reactions is sensitive to the activity of H_2O and O_2 .

Within the stability range of staurolite + quartz, the presence of kyanite indicates a minimum pressure range of 4-8 kbar (Holdaway, 1971). The stability of chlorite + quartz relative to talc + kyanite indicates a maximum pressure of 10-13 kbar (Schreyer and Seifert, 1969a). Lowering the activity of H_2O can significantly lower the pressure at which this reaction takes place (Newton and Wood, 1979). Mineral stabilities constrain temperatures to the range ≈ 550 - 700°C and pressures to ≈ 6 -11 kbar.

Geothermometry

Temperatures at Laurel Creek are estimated with the garnet-biotite geothermometers calibrated by Ferry and Spear (1978) and Goldman and Albee (1977). Ferry and Spear (1977) calibrated Fe-Mg partitioning

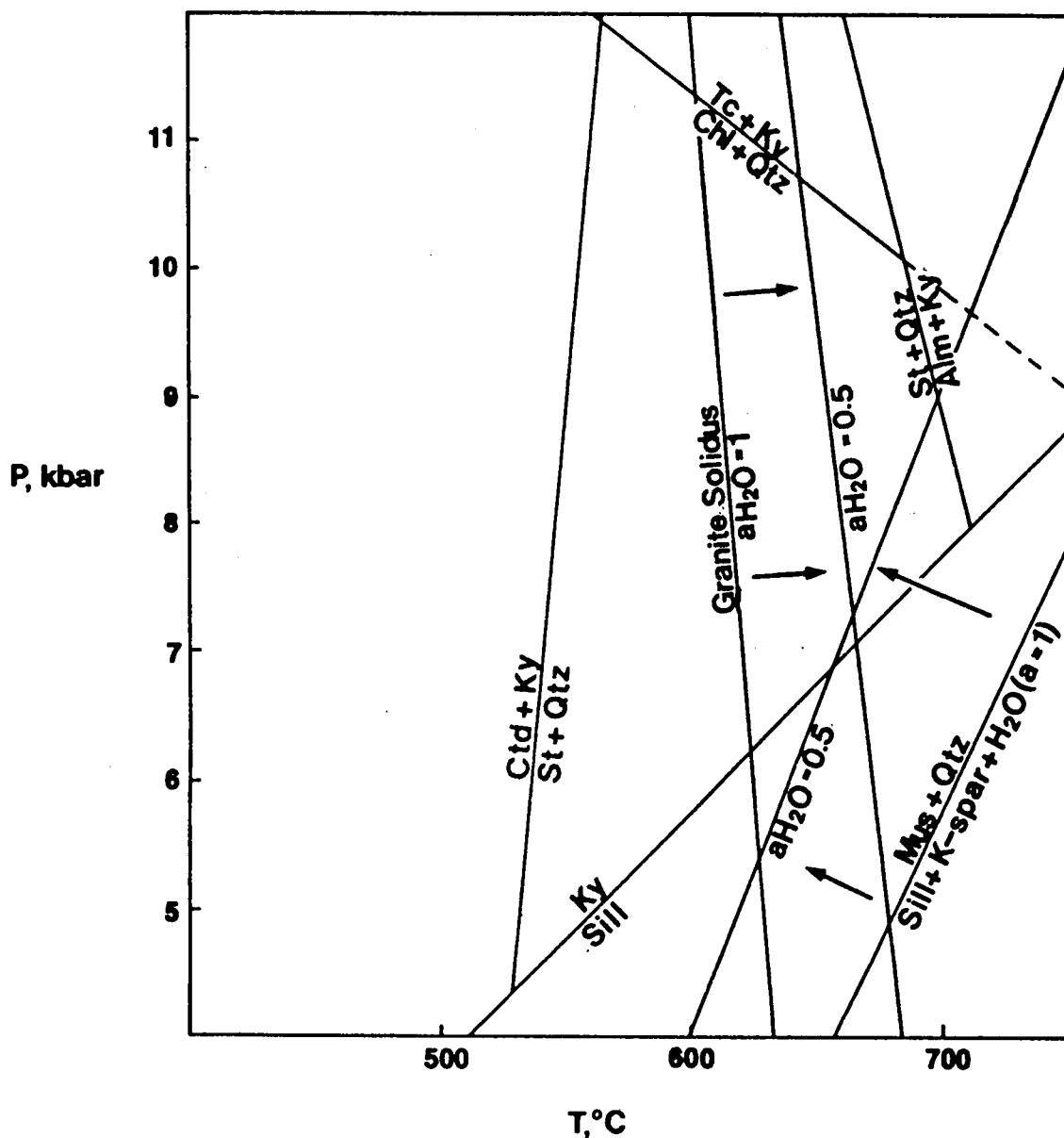


Figure 16. Reactions bracketing P-T conditions at Laurel Creek. The reactions bounding the upper and lower stability of staurolite + quartz are taken from Ganguly (1972). The upper stability of chlorite + quartz is taken from Schreyer and Seifert (1969). The kyanite = sillimanite reaction curve is taken from Holdaway (1971). The granite solidus and the upper stability of muscovite are taken from Kerric (1971).

between garnet and biotite in a simple binary system. The Goldman and Albee (1977) calibration was derived by correlation of natural garnet-biotite compositions with temperatures calculated by oxygen isotope fractionation between quartz and magnetite. In a semiquantitative manner, this approach takes into account Ca and Mn in garnet and Al^{vi} and Ti in biotite. Assuming a pressure of 7 kbars, the Ferry and Spear (1978) calibration for garnet-biotite pairs yields a temperature range of 540-653°C. These workers suggest exclusion of those pairs in which $(\text{Ca}+\text{Mn})/(\text{Ca}+\text{Mn}+\text{Fe}+\text{Mg})$ exceeds 0.20 in garnets or $(\text{Ti}+\text{Al}^{\text{vi}})/(\text{Ti}+\text{Al}^{\text{vi}}+\text{Fe}+\text{Mg})$ exceeds 0.15 in biotites (biotite compositions presented in Table A-4 in the Appendix). Sample L-73, the only pair meeting this criterion, yields a calculated temperature of 540°C. The Goldman and Albee (1977) calibration yields a temperature range of 399-680°C (Table 10). The highest and lowest temperatures are derived from the same garnet-biotite pairs for the respective calibrations. The lower temperature of 399°C seems unreasonable given the stability of staurolite relative to chloritoid. Excluding this aberrant value, the calculated temperature range is approximately 550-650°C, with a cluster of values at 600°C for both calibrations. The expected range in error reported by Ferry and Spear (1978) is $\pm 50^\circ\text{C}$.

Geobarometry

At a temperature of 600°C, pressures have been estimated using the following solid-solid reactions:

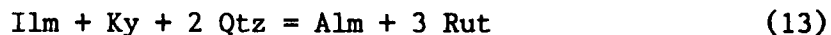


Table 10. Garnet-biotite Thermometry

Sample	Garnet			Biotite				T°,C	
	Mg/Fe	XMn	XC _a	Mg/Fe	XFe	XAl vi	XTi	G-Al	F-S2
L-73	0.274	0.017	0.129	1.728	0.328	0.095	0.024	399	540
L-77	0.232	0.112	0.076	1.255	0.364	0.130	0.038	632	601
L-63A	0.279	0.075	0.064	1.310	0.339	0.164	0.029	665	625
L-83	0.238	0.116	0.061	1.263	0.372	0.126	0.028	584	604
L-47	0.341	0.056	0.117	1.780	0.300	0.135	0.024	592	610

^aGoldman and Albee (1977).

^bFerry and Spear (1978).



Both reactions are multivariant due to the solid solution of other components; therefore, the application of proper activity-composition corrections is required.

Reaction (13) has been tightly bracketed by Bohlen et al. (1983a and b) and is particularly useful due to its relative insensitivity to temperature. From the assemblage garnet + ilmenite + rutile + quartz, found in amphibolite sample L-100, a minimum pressure is calculated by assuming the activity of absent kyanite to be 1. Sample L-100 contains one crystal of kyanite that is not interpreted as part of the prograde assemblage. Calculations were carried out using the endmember expression derived by Ghent and Stout (1984), from the experimental data of Bohlen et al. (1983a). A minimum pressure of ≈ 7 kbars is calculated assuming ideal solution for the mixing of almandine in garnet and FeTiO_3 in ilmenite. Deviation from ideality can significantly effect the calculated pressure. A minimum pressure of ≈ 9.7 kbar is calculated using the activity expression for ilmenite derived by Anderson and Lindsley (1981). The activity of almandine approaches ideality (Newton and Haselton, 1981). The ilmenite used for pressure calculation contains 14.2 mol. % hematite component and 9.3% geikielite component (composition presented in Table A-4 in the Appendix). The analyzed grain was optically homogeneous, with no signs of hematite exsolution(at 400X). This amount of hematite component is consistent with the ilmenite-hematite T-X diagram of Lindsley (1973). If all hematite is considered to be retrograde a minimum pressure of 6 kbar is calculated.

A pressure of $5.5\text{--}5.7 \pm 1.5$ kbar is calculated using the end member expression for reaction (14) and the activity-composition expressions for anorthite and grossular recommended by Newton and Haselton (1981) (Table 11). Potential error in this geobarometer arise from uncertainties in the endmember expression, the volume change, and the activity of grossular extrapolated down to low concentrations (Essene, 1982; Bohlen et al., 1983b). (For example, if the endmember expression of Goldsmith, 1980, recommended by Newton and Haselton, 1981, is replaced with the expression of Schmid et al., 1978, a pressure of 7.5 kbar is calculated.) Pelitic garnets may contain significant amounts of Mn. Incorporation of the Mn interaction parameter derived by Ganguly and Saxena (1984) have little effect on the calculated pressure. At 600 C° the kyanite-sillimanite reaction occurs at ≈ 5.7 kbar (Holdaway, 1971). Use of the garnet mixing data presented by Bohlen et al. (1983b) results in similar calculated pressures.

Although the geobarometer based on reaction (14) is commonly observed to be inconsistent with the aluminum silicate phase diagram (Newton and Haselton, 1981; Hodges and Spear, 1982, Ganguly and Saxena, 1984) it is doubted to be in error by 4 kbar. Because ilmenite is more likely to adjust to retrograde conditions, than garnet and plagioclase, the latter pressure calculation may be more reasonable; however, this geobarometer may have a range of uncertainty potentially as great as 2 kbar.

Table 11. Geobarometry

Sample	Calculated Pressures									
	Based on Reaction (1):									
	X_{al}	X_{py}	X_{gr}	X_{sp}	α_{al}^a	X_{il}	X_{gk}	X_{rm}	α_{il}^b	P, kbar
L-100	0.600	0.292	0.091	0.027	0.594	0.767	0.093	0.142	0.642	9.75
Based on Reaction (2)										
	X_{An}	α_{An}	X_{gr}	X_{py}	X_{al}	X_{sp}	α_{gr}	$\Delta \bar{V}$	P, Kbar	
L-36	0.894	0.858 ^a	0.095	0.236	0.628	0.041	0.120 ^a	64.69	5.49	
L-77	0.336	0.562	0.068	0.165	0.674	0.093	0.080	64.69	5.53	
L-63A	0.315	0.526	0.069	0.201	0.658	0.072	0.078	64.69	5.69	

^a α calculated from Newton and Haselton (1981).^b α calculated from Andersen and Lindsely (1981).

CHAPTER 5

CONCLUSIONS

The Laurel Creek amphibolite provides a fairly complete view of an amphibolite facies type for this grade of metamorphism. Chemographic analysis of amphibolite assemblages from Laurel Creek suggests that they are in reaction relationship with the common amphibolite assemblage hornblende + chlorite + garnet + epidote + oligoclase. Higher variance assemblages such as hornblende + chlorite + epidote + oligoclase should be permissible for Mg-rich compositions, whereas hornblende + garnet + epidote + oligoclase assemblages should be permissible for Fe-rich bulk compositions, at the same grade at which hornblende coexists with either kyanite, staurolite, or anorthite, or gedrite coexists with anorthite.

Although the presence of orthoamphibole suggests a low-Ca protolith, the coexistence of orthoamphibole with either hornblende + kyanite, hornblende + staurolite or calcic plagioclase may be related to the common amphibolite assemblage by reaction.

The paucity of assemblages similar to those found at Laurel Creek may be a function of metamorphic grade and bulk composition. It is possible that even though the conditions in many metamorphic terrains are such that the common assemblage is prohibited, many mafic compositions may be such that they cannot produce the assemblage hornblende + kyanite + staurolite + gedrite + anorthite. If this is the case then only high variance assemblages would result which do not prohibit the stability of the assemblage hornblende + gedrite + staurolite + kyanite

+ anorthite. It has been demonstrated that Laurel Creek amphibolite bulk compositions overlap the field defined by common or normal amphibolites from Vermont; also, bulk compositions (plotted on an ACF diagram) are within the phase volume hornblende + chlorite + epidote + oligoclase. Therefore, if bulk composition has an effect it is subtle.

The results of geothermometry and barometry are inconclusive. Temperatures are reasonably constrained to the range 550-650°C; however, pressure calculations from two different geobarometers yield conflicting results (5.5 ± 1.5 or 9.7 kbar). The fact that assemblages at Laurel Creek are in reaction relation to an assemblage common in many medium pressure terrains suggests pressures at least greater than ≈ 6 kbar.

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APPENDIX

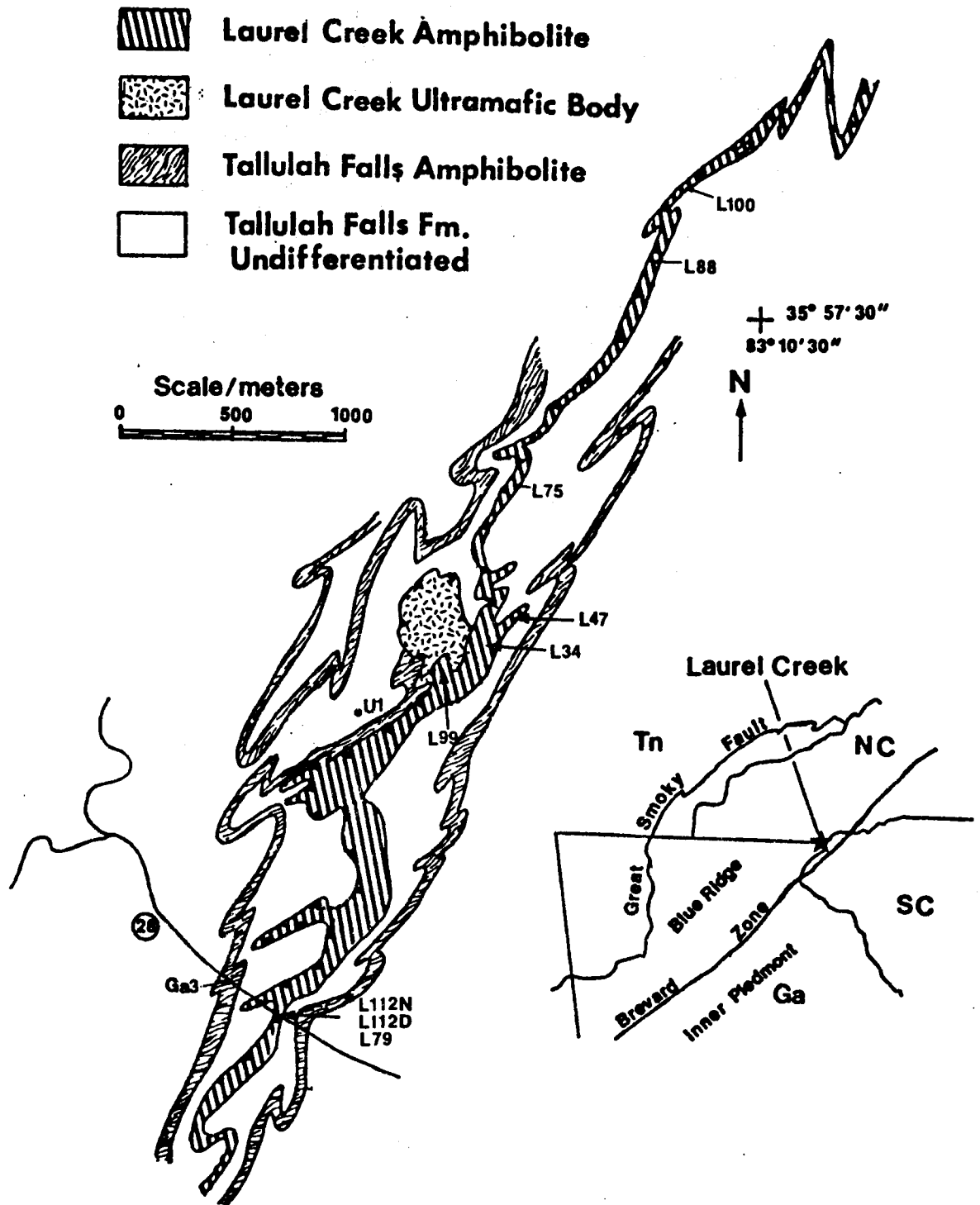


Figure A-1. Sample location map for samples analyzed with electron microprobe and XRF.

Table A-1. Replicate Analysis of Standard as Unknown With Best Reported Value

	USGS-BCR-1(7)			
	A	B	C	D
SiO	54.50	55.04	0.365	0.99
TiO2	2.20	2.15	0.358	2.27
Al2O3	13.61	13.60	0.014	0.07
FeO	13.46	13.06	0.130	2.99
MgO	3.46	3.24	0.175	6.24
MnO	0.18	0.20	0.003	10.00
CaO	6.92	6.77	0.060	2.17
K2O	1.70	1.72	0.047	1.41
Na2O	3.27	3.34	0.180	2.26
P2O5	0.36	0.36	0.032	0.56
Total	99.49	99.66		

A - Best Reported Value

B - Mean of 7 analysis of standard as unknown

C - Standard deviation of 7 replicate analysis

D - $((A - B)/A)(100)$

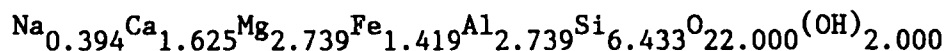
(# of replicate analysis

Table A-2. Mineral Abbreviations Used in Text

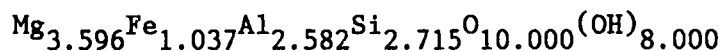
Alm	-	Almandine
An()	-	Plagioclase of An content ()
Anth	-	Anthophyllite
Bi	-	Biotite
Chl	-	Chlorite
Cord	-	Cordierite
Coru	-	Corundum
Gar	-	Garnet
Ged	-	Gedrite
Hbl	-	Hornblende
Ilm	-	Ilmenite
Ky	-	Kyanite
Qtz	-	Quartz
Rut	-	Rutile
Sill	-	Sillimanite
St	-	Staurolite

Table A-3. Mineral Compositions Used in Reactions Presented in Table 8 (p. 49)

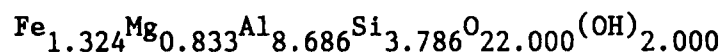
Hornblende



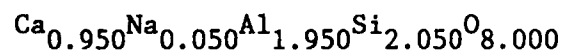
Chlorite



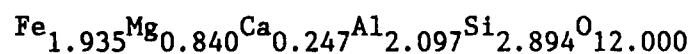
Staurolite



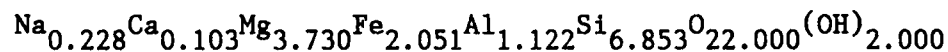
Anorthite



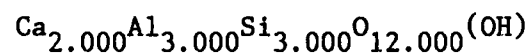
Garnet



Gedrite



Epidote



Oligoclase

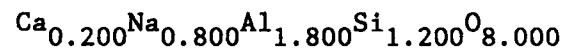


Table A-4. Biotite and Ilmenite Microprobe Compositions Used in Geobarometry and Thermometry

	Biotite					Ilmenite
	L-83(4)	L-63(3)	L-73(2)	L-77(3)	L-47(3)	L-100
SiO ₂	35.20	37.00	36.20	37.80	38.90	
Al ₂ O ₃	19.60	19.30	18.90	19.40	18.60	
TiO ₂	1.52	1.41	1.38	2.11	1.48	45.50
Fe ₂ O ₃	----	----	----	----	----	15.80
FeO	17.30	17.30	15.20	16.89	14.20	35.93
MgO	12.30	11.80	15.55	11.76	14.10	2.50
CaO	0.04	0.00	0.00	0.00	0.00	
K ₂ O	9.12	9.39	9.25	9.14	0.56	
Na ₂ O	0.50	0.41	0.23	0.51	0.13	
	95.58	96.61	96.71	97.61	96.97	99.73

Oxides normalized to 11(0) for biotite, 2(0) for ilmenite

Si	2.654	2.741	2.654	2.748	2.809	
Al	1.732	1.683	1.631	1.665	1.587	
Ti ⁺³	0.083	0.078	0.075	0.113	0.081	0.857
Fe ⁺²	-----	-----	-----	-----	-----	0.283
Fe ⁺²	1.086	1.060	0.932	1.027	0.857	0.767
Mg	1.375	1.301	1.700	1.274	1.523	0.093
Ca	0.002	0.000	0.000	0.000	0.000	
K	0.873	0.886	0.865	0.847	0.840	
Na	0.072	0.056	0.032	0.070	0.076	
Sum	7.877	7.805	7.889	7.744	7.773	2.000

Ferric iron in ilmenite is calculated on the bases of stoichiometry.

(#) = number of analysis.

VITA

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