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Kula C. Misra

K. C. Misra, Major Professor

We have read this thesis and
recommend its acceptance:

Harry G. McLean
Otto Kopp

Accepted for the Council:

LEwans Beth

Vice Chancellor
Graduate Studies and Research

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A PETROLOGIC AND GEOCHEMICAL STUDY OF SOME AMPHIBOLITE
BODIES IN THE SMITH RIVER ALLOCHTHON, VIRGINIA

A Thesis
Presented for the
Master of Science
Degree
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Jaikisan Achaibar

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ABSTRACT

The Smith River allochthon is located in the Inner Piedmont of Virginia. Distinct amphibolite units are present in the lowermost Bassett Formation of the allochthon. The amphibolite units are sandwiched between metasedimentary rocks: an underlying gneiss and an overlying mica schist. One hundred amphibolite samples were collected from different bodies exposed in three adjacent quadrangles: Sanville, Philpott, and Bassett. On the basis of petrographic studies of these amphibolite samples, 20 samples were selected for chemical analysis. The data are presented in this study.

Microprobe analyses have shown the amphiboles in the amphibolites to be calcic and chemically similar. Plagioclase composition is $An_{55}-An_{70}$ with smaller amounts of $An_{92}-An_{95}$. The major oxide phase is ferrian-ilmenite. T and P conditions of metamorphism for the amphibolites, based on phase assemblages and mineral compositions, are 535°-650°C and 3.5-4.5 Kb, respectively.

The amphibolites are interpreted to be metaigneous in origin on the basis of Niggli trend and bulk chemistry. The protolith of the amphibolites was probably a quartz tholeiite, as judged from the AFM diagram and normative mineralogy. Discriminant diagrams based on major and trace

elements suggest that the parental basalt was formed within a continental rift environment. This is consistent with the Late Precambrian tectonic history inferred for this part of the Appalachian orogeny.

TABLE OF CONTENTS

CHAPTER	PAGE
1. INTRODUCTION	1
Purpose of Study	1
Methods of Study	4
2. GEOLOGIC SETTING	10
Lithologies and Stratigraphy	10
Structure	13
Metamorphism	14
Field Relations of Amphibolites	16
3. PETROLOGY OF THE AMPHIBOLITES	19
Petrography	19
Mineral Chemistry	26
Conditions of Metamorphism	31
4. PETROGENESIS	47
Amphibolite Protolith and Chemical Affinities	47
Tectonic Setting	57
Tectonic Setting and the Appalachian Orogen	63
Summary	66
REFERENCES	67
APPENDICES	78
APPENDIX A	79
APPENDIX B	86
APPENDIX C	88
APPENDIX D	90
VITA	93

LIST OF TABLES

TABLE	PAGE
1. Geologic Formations in the Snow Creek, Martinsville East, Price, and Spray Quadrangles (after Conely and Henika, 1973)	11
2. Cation Distribution in Amphiboles from Smith River Allochthon	27
3. Whole Rock Chemical Analyses of 12 Representative Amphibolite Samples from the Smith River Allochthon	49
A-1. Representative Microprobe Analyses of Amphiboles with Recalculation of Cation Distribution (after Leake, 1978)	82
A-2. Representative Microprobe Analyses of Amphiboles with Recalculation of Cation Distribution (after Papike et al., 1974)	83
A-3. Electron Microprobe Analyses of Amphiboles (Sample Averages) with Recalculation of Cation Distribution (after Papike et al., 1974)	85
B-1. Representative Microprobe Analyses of Plagioclase Coexisting with Amphiboles	87
C-1. Representative Microprobe Analyses of Fe-Ti Oxides	89
D-1. Correspondence between Field and Lab Numbers of Samples Plus Sample Location Map	92

LIST OF FIGURES

FIGURE		PAGE
1.	A Generalized Geologic Map of the Piedmont Showing the Smith River Allochthon and Location of the Quadrangles (Sanville, Philpott, Basset) from Which Samples Were Obtained for This Study	2
2.	Map Showing Distribution of the Amphibolite Bodies and Sample Locations in the Sanville, Philpott and Bassett Quadrangles, Smith River Allochthon, Virginia	6
3.	Photomicrographs of Amphibolite Lithologies . .	21
4.	Ca-Mg-Fe Diagram Showing Compositions of Coexisting Amphiboles and Plagioclases from Amphibolites of the Smith River Allochthon	28
5.	Plot of $Al^{VI} + Fe^{3+} + Ca^A$ versus A Site Occupancy of the Amphiboles from the Smith River Allochthon (after Pamic et al., 1972)	29
6.	FeO-Fe ₂ O ₃ -TiO ₂ Ternary Plot of Oxide Assemblage in Amphibolites of the Smith River Allochthon	32
7.	Na ₂ O + K ₂ O versus TiO ₂ for Amphiboles from the Smith River Allochthon	33
8.	X _{Ab} in Plagioclase versus X _{Na(A)} in Coexisting Amphibole (Spear, 1981a) from the Smith River Amphibolites	35
9.	Variation Diagrams Showing Amphibole Compositions in the Sanville, Philpott, and Bassett Quadrangles Amphibolites, Smith River Allochthon	37
10.	Distribution of Al^{IV} (Amphibole) versus Ca/Ca + Na (Plagioclase) for Coexisting Amphibole and Plagioclase (Saxena, 1968) in the Smith River Amphibolites and X _{Na(A)} in Amphiboles versus X _{Ab} in Plagioclase for the Smith River Amphibolites with Hypothetical Contours as Temperature Determinants (Spear, 1981a)	41

FIGURE	PAGE
11. Histogram of Ti Content, Weight Percent Oxide, of Metamorphic Amphiboles versus Number of Analyses (Raase, 1974) Compared to a Histogram of Ti Content, Weight Percent Oxide, of Amphiboles from the Smith River Allochthon	44
12. P_f -T Relations (Spear, 1981b) for Amphiboles from the Smith River Allochthon at Oxygen Fugacities Defined By: the QFM and the WM Buffers	46
13. Niggli 100 mg-c-(al-alk) Plot for the Amphiboles from the Smith River Allochthon Compared with the Trends Observed for Igneous Rocks and Pelite-Carbonate Mixtures (after Leake, 1974)	51
14. Al + Fe + Ti versus Ca + Mg and (Al + Fe + Ti)/3 - K versus (Al + Fe + Ti)/3 - Na Discriminant Diagrams (Bard and Moine, 1979) for Amphibolites from the Smith River Allochthon	52
15. CIPW-Normative Compositions of Amphibolites from the Smith River Allochthon in Terms of the Basalt Tetrahedron of Yoder and Tilley (1962)	54
16. AFM Plot of the Smith River Amphibolites	55
17. Selected Major Element Oxides and Trace Elements Plotted Against Niggli mg Number for the Smith River Amphibolites	56
18. TiO_2 versus Y/Nb and Nb/Y versus Zr/ P_2O_5 Discriminant Diagrams (after Floyd and Winchester, 1975) for the Smith River Amphibolites	59
19. Comparison of Abundances of Trace Elements in Amphibolites from the Smith River Allochthon to Modern Basalts and to Other Metabasalts (adapted from McLean et al., 1981)	60

FIGURE	PAGE
20. Ti/100-Zr-Yx3 Discriminant Diagram (Pearce and Cann, 1973) for the Smith River Amphibolites	62
D-1. Nomenclature of Smith River Allochthon Amphiboles (after Leake, 1978)	91

LIST OF PLATES

PLATE

1. Sample Location Map In Pocket

CHAPTER 1

INTRODUCTION

Purpose of Study

The Smith River allochthon is a northeast-southwest trending belt within the Inner Piedmont of southcentral Virginia and with some extension into North Carolina (Figure 1). Its northeast extent in Virginia is uncertain. This allochthon is located between the Blue Ridge and Sauratown Mountains anticlinoria. According to Brown (1958), the synclinal structure which contains the allochthon lies along the axial trace of the James River synclinorium.

The oldest rocks in the allochthon are the Bassett and Fork Mountain Formations (Conley and Henika, 1973). The Bassett Formation consists of leucocratic biotite gneiss overlain by amphibolite. Some thin amphibolite units also occur as conformable bands within the gneiss. Mica schist, the lowermost unit of the overlying Fork Mountain Formation, is in direct contact with the Bassett amphibolite unit. The amphibolites are of uncertain age and have been considered to be Precambrian on the basis of stratigraphic correlations (Conley and Henika, 1973, 1970; Henika, 1972; Conley and Toewe, 1968).

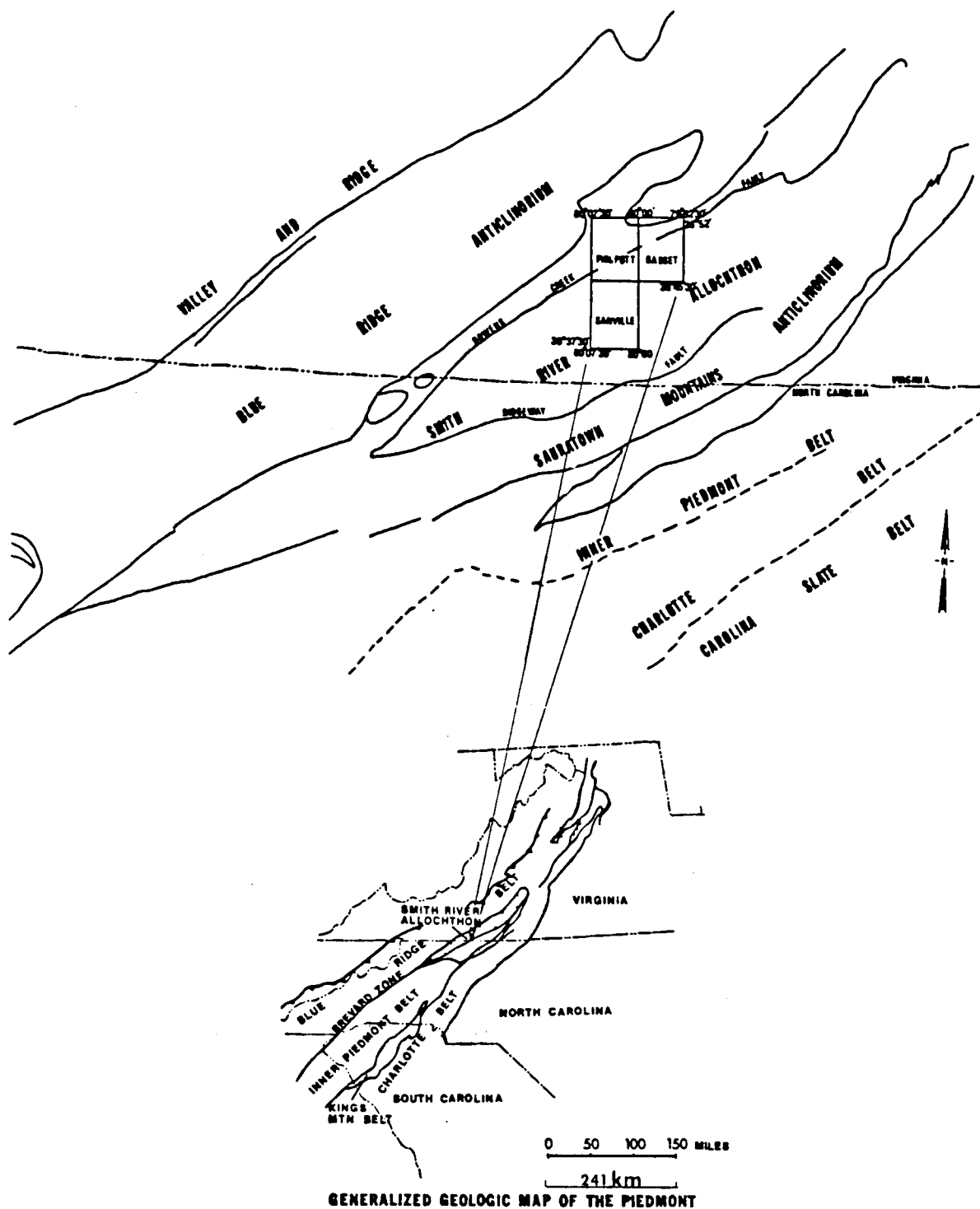


Figure 1. A generalized geologic map of the Piedmont showing the Smith River allochthon and location of the quadrangles (Sanville, Philpott, Basset) from which samples were obtained for this study. Modified from Pavlides (1981).

In central Virginia, Pavlides (1981) has defined a volcanic-plutonic belt of pre-Ordovician age which consists of metasedimentary and metavolcanic rocks (amphibolites) and associated metamorphosed intrusives. The Smith River allochthon may represent a southwest extension of this volcanic-plutonic belt. However, Pavlides (1981) has concluded that the volcanic-plutonic belt is probably early Cambrian in age and was formed in an island-arc environment. If such is the case, the Smith River Allochthon (Precambrian) may not be an extension of the central Virginia belt and probably originated under totally different conditions.

The Smith River allochthon has been subjected to Barrovian type regional metamorphism at almandine-amphibolite facies (Conley and Henika, 1973). This peak metamorphic episode was followed by a later episode of retrogression to greenschist facies. Also, it has been observed that minerals and textures show locally different sequences of crystallization and deformation which suggest variation of metamorphic controls from place to place (Rankin et al., 1973) or differences in bulk composition of the premetamorphosed rocks.

It has been suggested that the amphibolites in the Smith River allochthon are metamorphosed products of mafic volcanic rocks or impure dolomite beds. A geochemical and petrological study of several amphibolite bodies within the

Sanville, Philpott, and Bassett 7½ minute quadrangles was undertaken with the following objectives:

1. to examine petrographic and chemical variations in amphiboles with respect to geographic distribution of the amphibolite bodies and to estimate the probable conditions of metamorphism;
2. to interpret the origin (igneous or sedimentary) of the amphibolites; and
3. to discuss the significance of the data in terms of the paleotectonic environment of the allochthon.

Methods of Study

Fieldwork within the Sanville, Philpott, and Bassett quadrangles (Figure 1) consisted of collecting samples from the amphibolite bodies outlined by Conley and Henika (1973, 1970), Henika (1971), and Misra and Keller (unpublished work). These amphibolite bodies are well mapped within the Philpott and Bassett quadrangles; the mapping of the amphibolite bodies in the Sanville quadrangle by Misra and Keller has not been completed.

Most of the amphibolites are highly weathered with a cover of soil and commonly of vegetation. Collection of fresh samples was difficult because of the weathered nature of the amphibolite bodies, and this prevented collection of fresh samples from all the amphibolite bodies. Locations of

fresh samples collected for this study are shown in Figure 2 and Plate 1 (in pocket).

One hundred amphibolite samples were collected, representing the geologic and geographic distribution of the amphibolite bodies within the study area. These were cut perpendicular to foliation, and thin sections were studied petrographically using transmitted light. Of these, 50 sections were polished and studied under reflected light. Based upon these petrographic studies of mineralogy and textural relationships, 20 representative sections were selected for electron microprobe analysis.

Microprobe analyses were carried out using an automated MAC 400S electron microprobe, using both natural and synthetic standards. During analyses, the accelerating voltage was 15 KV. A beam current of 0.03 A and a defocused beam of about 10 μm were used in analyses of amphiboles and plagioclase, while a beam current of 0.05 A and a focused beam of about 1 μm were used to analyze the oxide phases. The microprobe data were reduced using the correction procedure of Bence and Albee (1968) and Albee and Ray (1970).

For each thin section, four to six amphibole grains were analyzed. On each grain, at least three to six analyses were performed and an average taken. Plagioclase and accessory oxide phases (ilmenite, magnetite and

Figure 2. Map showing distribution of the amphibolite bodies and sample locations (●) in the Sanville, Philpott and Bassett quadrangles, Smith River allochthon, Virginia. (■) denotes samples used for electron microprobe analysis, (★) denotes samples used for whole rock chemical analyses.

Sources: Henika, 1971; Conley and Henika, 1973; unpublished map of Misra and Keller.

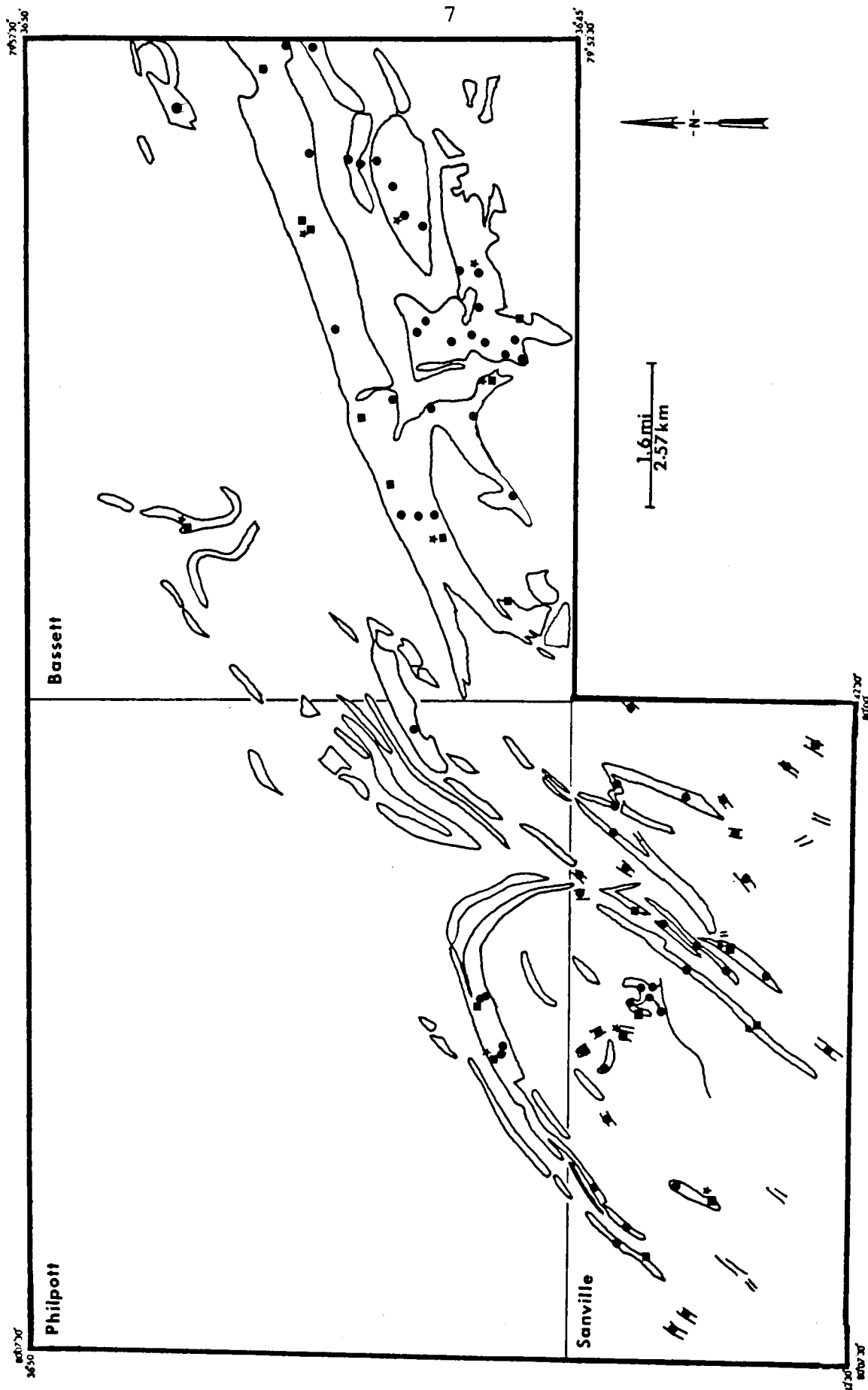


Figure 2.

hematite) were analyzed less extensively (2 to 3 grains per thin section; 3 to 4 points in each grain). Average values and standard deviations were computed (Appendices A, B and C).

The amphibole analyses were recalculated using a computer program of Papike et al. (1974) and also by the method suggested by Leake (1978). Comparison between the method of Papike et al. (1974) and Leake (1978) indicate differences in the cation proportions assigned to the amphibole structure on the basis of Fe^{3+} determined from each method (see Appendix A, Tables A-1 and A-2). However, the cation proportions of the amphiboles obtained by using the recalculation procedure of Papike et al. (1974) are used for all discussion in the Text (see Appendix A).

The amphibole composition in each thin section of this study is represented by summing the average values of each of the amphibole grains analyzed in that thin section and determining a final average for the thin section (Appendix A, Table A-3). Such an average is a meaningful representation of the amphibole composition in a thin section because of the relatively small compositional variations among the different grains of a thin section. The final average values were used for Papike et al. (1974) recalculation procedure. Nomenclature of the amphiboles are from Leake (1978). The Fe^{2+} and Fe^{3+} in the iron-titanium oxide phases were calculated by the method of Carmichael (1967).

Twelve amphibolite samples were chosen (on basis of the petrography and phase composition) for analyses of bulk chemistry (SiO_2 , Al_2O_3 , CaO , MgO , Na_2O , K_2O , Fe_2O_3 , MnO , TiO_2 , P_2O_5 , Cr , Rb , Sr , Y , Zr , Nb , Ba , Sc , Ni , La , Yb , Hf , Ta , and Th). It is believed that these 12 samples (see Figure 2) encompass the regional variations in the study area. The chemical analyses were done commercially at the XRAL Lab, Don Mills, Canada. Whole rock analyses for major elements (SiO_2 , Al_2O_3 , CaO , MgO , Na_2O , K_2O , Fe_2O_3 , MnO , TiO_2 , and P_2O_5) and trace elements (Cr , Rb , Sr , Y , Zr , Nb , and Ba) were done on a Phillips PW 1600 simultaneous X-ray fluorescence spectrometer. This system has been calibrated using more than 40 reference materials. Instrument precision for these elements is $\pm 0.5\%$. Trace elements (Sc , La , Yb , Hf , Ta , and Th) were analyzed by neutron activation, using a multichannel analyzer with a pacified hyperpure germanium detector. Ni was determined using AA instrumentation. Instrumental precision neutron activation and AA analyses are within $\pm 10\%$. CIPW norm and Niggli calculations were computed, assuming $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio = 0.71 (McElhaney, 1981, ms).

CHAPTER 2

GEOLOGIC SETTING

Lithologies and Stratigraphy

Table 1 shows the correlation of formations and intrusions in the Smith River allochthon with those of the Blue Ridge anticlinorium and the Sauratown Mountains anticlinorium. The stratigraphic uncertainties within these structures are a result of associated structural complexities.

The prominent amphibolite unit in the study area forms the upper unit of the Bassett Formation. The amphibolite is overlain by the lowest unit (mica schist) of the Fork Mountain Formation. The Bassett Formation is interpreted as the lowest unit of the allochthon which is exposed at the surface. However, the stratigraphic position of the Bassett Formation with respect to the overlying units may be questionable because of the complex folding present in the allochthon (Conley and Henika, 1973; Misra and Keller, pers. comm., 1981).

The unit which underlies the amphibolite in the Bassett Formation is a leucocratic biotite gneiss. This gneiss is generally equigranular, medium-grained, light- to medium-grey, with biotite dispersed through a leucocratic groundmass.

Table 1. Geologic formations in the Snow Creek, Martinsville East, Price, and Spray quadrangles (after Conley and Henika, 1973).

Age	Blue Ridge Anticlinorium	Sauratown Mtns. Anticlinorium	Smith River Allochthon
Quaternary	Alluvium	Alluvium	Alluvium
	Alluvial-terrace deposits	Alluvial-terrace deposits Colluvium	Alluvial-terrace deposits Colluvium
Triassic		Diabase dikes	Diabase dikes
Precambrian (?)		Alaskite, pegmatite, and leuco-quartz diorite Altered metapyroxene and talc schist	Alaskite, pegmatite, and leuco-quartz diorite Talc-tremolite schist, in part metapyroxenite
Precambrian	Lynchburg Formation (820 million years old)	Gneiss and mica schist muscovite and muscovite-biotite gneiss garnet-mica schist	Rich Acres formation (younger part) norite-diorite Leatherwood Granite (1020 million years old) Rich Acres formation (older part) gabbro Fork Mountain formation biotite gneiss mica schist Bassett formation amphibolite leucocratic biotite gneiss
	Major unconformity	Major unconformity	
	Moneta gneiss (1000 million years old)	Granitic augen gneiss (1192 million years old)	

The gneiss is commonly segregation-banded with well-defined, alternating feldspar-rich and biotite-rich layers. The typical mineral assemblage is plagioclase, quartz, biotite. Smaller amounts of sphene, magnetite, muscovite, microcline, zircon, and epidote are present.

Mica schist of the Fork Mountain Formation is in contact with the amphibolite of the Bassett Formation. This schist is light- to medium-grey, generally porphyroblastic, fine- to medium-grained, and has some segregation banding. The schist is composed mostly of sericite with smaller amounts of muscovite porphyroblasts and quartz. Other minerals present are chlorite, cordierite, staurolite, sillimanite, garnet, limonite, tourmaline, magnetite and zircon.

The amphibolite is generally foliated to massive, medium- to fine-grained, and equigranular. The colors range from almost black (composed mostly of amphibole) to dark-grey (salt and pepper effect produced by intermixing of amphibole, plagioclase and quartz grains) to greenish-black (chlorite formed from the breakdown of amphibole during retrograde metamorphism). In addition to the major minerals (amphibole, quartz, and plagioclase), accessory sphene, epidote, and ilmenite are present. A few samples also have hematite, magnetite, pyrrhotite, chalcopyrite, pyrite and garnet as minor phases. Retrograde chlorite and minute

amounts of biotite and sericite are also present in a few samples.

Structure

From their studies and mapping of the geology of the Snow Creek, Martinsville East, Price and Spray quadrangles within the allochthon in Virginia, Conley and Henika (1973) favored the interpretation that the allochthon represents a complexly folded sheet. However, they recognized that the structure could also be interpreted either as the upper limb of a detached recumbent fold nappe with an almost horizontal fold axis overturned to the northeast, or as the bottom limb of a recumbent fold overturned to the southeast. The timing of movement of the Smith River allochthon is not understood; it may be related to the Brevard fault zone to the southeast (Conley and Henika, 1973). Its relation to the Sauratown Mountains anticlinorium is also unknown (Espenshade et al., 1975; Hatcher, 1975).

The major structure of the Smith River allochthon is a broad open synform. This synformal structure is thought to have been produced during a later deformational episode rather than the earlier episode which was responsible for the antiformal nature of the allochthon as a whole (Henika, 1971).

The complex internal structure of the allochthon is dominated by polyphase folds, some of which predate the emplacement of the allochthon. Henika (1971) concluded that the early sets of folds were isoclinal. These folds have subhorizontal axial planes; the later sets of folds generally display overturned antiforms and synforms.

Conley and Henika (1973) suggested that the earliest orogenic event occurred prior to the 1020 m.y. emplacement ages of the Rich Acres and Leatherwood Granite intrusives. During this early orogenic event, units which were the protoliths of the Bassett Formation and the Fork Mountain Formation and are now present at the base and near the basal section of the allochthon, respectively, were warped into a series of elongate, generally overturned recumbent folds. These elongate folds were refolded into a series of low amplitude, open to overturned structures. The final product of this polyphase folding was the complexly folded anti-formal structure containing the Bassett Formation in the core which completely wraps around a shallow synform with the Fork Mountain Formation at its core.

Metamorphism

The regional metamorphism of the Smith River allochthon is of the Barrovian type at almandine-amphibolite facies (Conley and Henika, 1973). This Barrovian type of

metamorphism is typical of the Inner Piedmont as a whole. Following the peak metamorphic episode, the rocks were retrograded to greenschist facies which is also typical for the Inner Piedmont. It is unknown whether retrograde metamorphism immediately followed prograde metamorphism during the same tectonic event or whether retrogression occurred during a separate tectonic event (Rankin et al., 1973; Conley and Henika, 1973).

Conley and Henika (1973) used metamorphic index minerals to define various metamorphic zones within the allochthon. According to them, rocks along the northwestern border of the allochthon reached staurolite grade, whereas in the central and southern parts of the allochthon they reached sillimanite grade.

Timing of the peak metamorphic episode in the allochthon is problematical. Two dates have been inferred on the basis of zircon discordant age and Rb-Sr whole rock ages from the Leatherwood Granite which intruded the metamorphosed Bassett and Fork Mountain Formations. Conley and Henika (1973) have dated the Leatherwood Granite intrusion as 1020 m.y. old (Zr discordant age) and concluded that peak metamorphism occurred in an orogenic event prior to the intrusion. Odom and Russel (1975) have dated the Leatherwood granite (whole rock Rb-Sr isochron age) as 464 ± 20 m.y. old and concluded that the peak metamorphic

episode occurred close to 450 m.y. ago. There are no other independent age determinations, thus, it is difficult to eliminate either of the two dates that have been proposed for the peak metamorphic episode. However, the date given by Odom and Russel (1975) is favored as it is compatible with the tectonic models recently suggested for the Southern Appalachians.

Field Relations of Amphibolites

The exposed amphibolite units of the Bassett Formation occur as discontinuous bodies which range from narrow bands to elliptical lenses (Figure 2, p. 6); a few of the larger bodies extend for several kilometers. The amphibolite bodies are conformable with the underlying leucocratic biotite gneiss and the overlying mica schist units.

Contacts between the amphibolites and the enclosing felsic units (gneiss and/or schist) are not commonly observed throughout the study area, but where exposed, the contacts are usually sharp and parallel to regional foliation (Conley and Henika, 1973). Sharp contacts and the absence of obvious gradational or transitional lithologies between amphibolites and felsic rocks suggest that the amphibolites were derived from a distinct rock type rather than from a carbonate-shale mixture (Stephenson and Hensel, 1982).

Like the rest of the lithologic units, the amphibolite bodies conform to the regional structure. Folding in the amphibolites range from microscopic crenulations along axial regions of folds to smaller folds seen in outcrops, and finally to larger folds determined only by regional mapping. Few of the smaller folds are ptygmatic, mostly up to a few centimeters across. Some amphibolite bodies are cut by alaskite and pegmatitic dikes and sills. discontinuous segregation bands are also present in some of the amphibolite bodies. Conley and Henika (1973) have observed some rare features which resemble graded bedding and cut-and-fill structures where the rock is composed of alternating light (plagioclase-rich) and dark (amphibole-rich) layers.

There are no obvious field relations or fabric which will establish the protolith from which the amphibolites were derived. Segregation banding may represent premetamorphic sedimentary layering or a product of metamorphic differentiation. The supposed cut-and-fill features described by Conley and Henika (1973) are too restricted spatially to be considered an evidence for sedimentary origin of the amphibolites on a regional scale. Orville (1969) suggested that amphibolites can be formed by metasomatism of impure calcareous and/or dolomitic sediments. This may be true only for very thin bands or layers of amphibolites; evidence for a similar origin for

much thicker and more extensive amphibolite bodies is absent in most metamorphic terrains (Stephenson, 1981).

Within the host rocks (gneiss and schist), the compositional layers probably represent strata of premetamorphic rock sequence; hence, the amphibolitic bodies that alternate with the layered gneiss and schist could be interpreted as part of the original rock sequence or as volcanic flows or sills.

In summary, the field relations observed within the study area offer no unambiguous conclusion about the origin of the amphibolites. A chemical investigation has been attempted in this study to determine the protolith from which the amphibolite was derived.

CHAPTER 3

PETROLOGY OF THE AMPHIBOLITES

Petrography

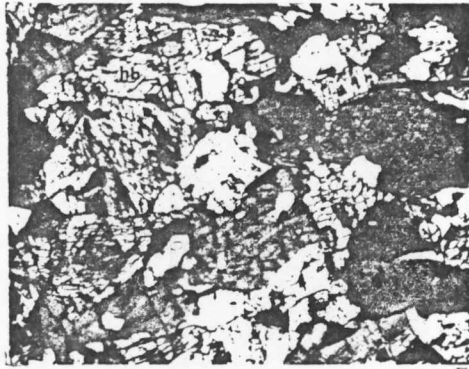
For descriptive purposes, the amphibolites may be classified into two textural types: (1) granoblastic, and (2) foliated. Grain sizes are usually 0.2 to 0.3 mm. Narrow discontinuous bands of quartz and plagioclase, although not ubiquitous, are commonly discernable in thin sections. Except for a few samples (for example, AB25, AS3) which contain just a few quartz grains, the quartz content seems relatively constant (about 3%), but the amounts of amphibole and plagioclase do vary noticeably. Such modal variations may be due to differences in bulk composition or local metamorphic grade (Engel and Engel, 1962). In some cases, the amphibolite is composed almost wholly of amphibole with little plagioclase and quartz. In general, however, amphibole roughly constitutes two-thirds of the amphibolite specimens studied.

The typical equilibrium assemblage is amphibole-plagioclase. Equilibrium among the coexisting phases is indicated by textural evidence (sharp boundary contacts, lack of intergrowths among the mineral phases, and absence of secondary reactions), and chemical homogeneity within

grains (absence of zonation within grains). Megascopically, polyphase deformation of the amphibolite bodies is easily recognized. However, on the microscopic scale, deformational features are almost totally absent as suggested by the lack of the following features: undulose extinction in quartz, crushed breccias, twinning in amphibole, deformed twins in plagioclase, and rolled porphyroblastic structures. One sample (AS27) contains garnet with the garnet porphyroblasts flattened parallel to foliation. Another sample (AP3) showed prismatic amphibole grains with crenulations, but this sample was taken close to the axial region of a fold. Very few plagioclase grains show deformation of pericline-albite twins.

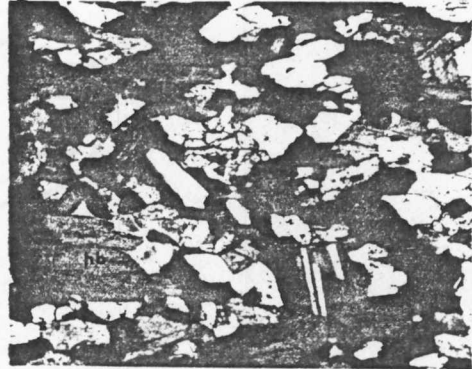
Typically, the granoblastic amphibole displays smoothly curved to straight polygonal boundaries with quartz, plagioclase and other amphibole grains (Figure 3A), and triple junctions with approximately 120° angles which suggest textural equilibrium (Winkler, 1979; Spry, 1969). The amphibole is strongly pleochroic, usually brown- to yellow-brown to green. Most of the granoblastic amphibole grains contain inclusions of sphene, ilmenite, plagioclase and quartz. The foliated amphibole (Figure 3B), which is also pleochroic from brown to green, occurs as narrow, elongated prisms with ragged, indistinct terminations; in some instances, the amphibole appears as stubby xenoblastic

Figure 3. Photomicrographs of amphibolite lithologies. Scales are shown at bottom of figure. (A) Granoblastic texture in amphibolites. Crossed nicols. (B) Foliated texture in amphibolites. Crossed nicols. (C) Ilmenite rimmed by sphene. Reflected light. (D) Euhedral sphene common in amphibolites. Crossed nicols. (E) A grain of hemo-ilmenite (il)/ilmeno-hematite (hm). Reflected light.



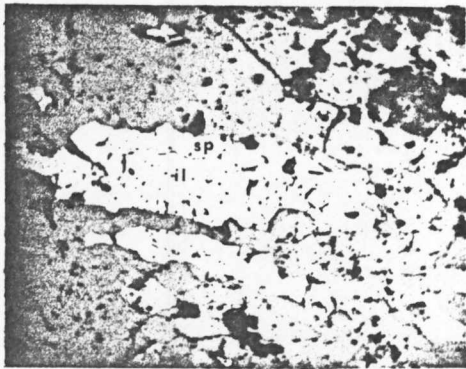
a

1 mm



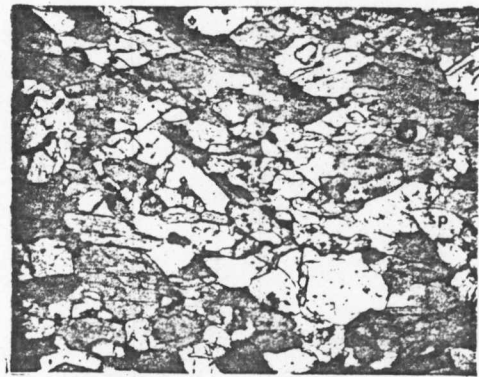
b

1 mm



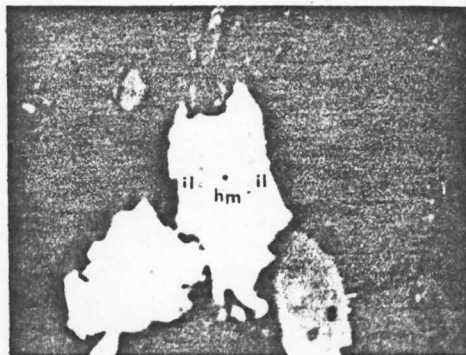
c

0.5 mm



d

1 mm



e

0.5 mm

Figure 3.

grains, but the longer dimensions show a preferred orientation. Usually, the amphibole encloses varying amounts of plagioclase, quartz, sphene and ilmenite inclusions.

Plagioclase occurs as fresh, equant and tabulate grains, generally untwinned, but sometimes with albite and combined albite and pericline twins. Some of the plagioclase grains contain inclusions of other plagioclase grains and also quartz. In a small number of sections, some plagioclase grains appear cloudy, apparently with some epidotization (?) or saussuritization (?). The plagioclase grains are unzoned and most of them are generally intergranular to the amphibole grains. There is also some association with quartz in narrow segregation bands.

Quartz occurs as clear, lenticular or xenoblastic grains. The quartz is usually an accessory phase which is intergranular to amphibole and plagioclase. Occasionally, the quartz is an included phase in amphibole and plagioclase. In a few sections, the quartz is associated with plagioclase, forming narrow, felsic, light-colored bands. These segregation bands are probably the result of metamorphic differentiation.

Epidote ($\pm$ zosite) is an accessory phase in many of the thin sections. It occurs as equant, xenoblastic grains and is intergranular to the other phases. The association,

intergranular texture, and sharp boundaries with the major phases suggest that most of the epidote is primary; a small proportion of the epidote may be a later retrograde product after plagioclase.

Ilmenite is an ubiquitous phase in the amphibolites of the study area. The ilmenite occurs as elongated, intergranular grains parallel to the orientation of the major phases in the foliated amphibolites or as irregular to rounded inclusions in the amphiboles. In the granoblastic amphibolites, the ilmenite occurs as irregular, amoeboid blebs intergranular to the amphiboles and also as rounded to irregular inclusions within the amphibole grains. Much of the ilmenite in some sections is partially or completely rimmed by sphene (Figure 3C), presumably formed as a late metamorphic reaction product (Engel et al., 1966). Spear (1981b) interpreted such texture to represent a reaction relationship between sphene and ilmenite with decreasing temperature. This reaction relationship between the sphene and ilmenite may be a product of decreasing temperature after peak metamorphism, or the product of later retrograde metamorphism at lower temperature.

Sphene is another ubiquitous phase in the amphibolite, although its modal abundance varies considerably among samples. In all cases, however, the sphene occurs as euhedral grains, mostly as inclusions in amphiboles, with

some being interstitial to the amphiboles. In a few thin sections, trains of sphene are present (Figure 3D).

Pyrrhotite grains are present in samples restricted to a small area with the Sanville quadrangle (AS13, 14, 15, 16, 17, 18). The grains are usually small, irregular, and disseminated interstitially to the amphibole grains. Some pyrrhotite grains are also present as inclusions in the amphiboles. Associated with the pyrrhotite are minute, exolved (?) blebs of chalcopyrite. In a few cases, the chalcopyrite is dissociated from the pyrrhotite.

Coexisting hematite-magnetite-ilmenite phases have been observed in a few samples. This assemblage is indicative of a high grade of metamorphism (Rumble, 1976). In most instances, the magnetite occurs as single-phase grains, whereas the other oxides occur as hemo-ilmenite and ilmeno-hematite intergrowths (Figure 3E). The magnetite occurs either as isolated grains or in contact with hemo-ilmenite but never in contact with the ilmeno-hematite. Several of the Fe-Ti oxide grains show half of the grain composed of hemo-ilmenite host with ilmeno-hematite blebs; other grains show half of the grain composed of ilmeno-hematite host with hemo-ilmenite blebs. These relationships suggest that simple subsolvus exsolution occurred in these phases.

Mineral Chemistry

Representative analyses of amphiboles, plagioclase, and Fe-Ti oxides in the studied amphibolites are presented in Appendices A, B and C. Table 2 shows the distribution of the cation site occupancies in the amphibole formulae calculated with the procedure of Papike et al. (1974). Compositions of amphibole and coexisting plagioclase are shown in Figure 4.

The amphiboles are all calcic, with $(Ca + Na) > 1.34$ and $Na^{M4} < 0.67$ (Leake, 1978). Most classifications of amphiboles depend on the amount of substitution of Al and Fe^{3+} for Si, or the replacement of Mg by Al, Fe^{3+} , Ti, and Fe^{2+} as well as the number of cations in the A site. Pamić et al. (1973) suggest that a plot of $(Al + Fe^{3+})^{VI} + Ca^A$ versus A site occupancy, projected onto a diagram with edenite, pargasite, tschermakite and common hornblende (Ca, Mg, Al, $SiO_{23}H_2O$) as end members, will cover the whole range of magnesium to iron ratios in natural amphiboles. Such a plot for the amphiboles of the Smith River allochthon (Figure 5) shows that they resemble the common hornblendes (Hb) of Pamić et al. (1973). With the exception of a few samples (see Appendix) the amphiboles are magnesio-hornblendes according to the nomenclature proposed by Leake (1978). It is apparent that there is compositional variation among the amphiboles, the amphiboles from the Philpott and Bassett

Table 2. Cation distribution in amphiboles from Smith River allochthon.

Sample No.	Si	Al ^{IV}	Al ^{VI}	Fe ²⁺	Fe ³⁺	Mg	Mn	Ti	Ca	Na ^{M4}	Na ^A	K ^A	Sum
AS29	6.55	1.45	0.59	1.74	0.61	2.13	0.03	0.09	1.65	0.15	0.15	0.08	98.38
AS27	6.90	1.10	0.59	2.04	0.19	2.10	0.02	0.11	1.81	0.14	0.15	0.09	93.99
AS13	6.72	1.28	0.67	1.41	0.39	2.42	0.03	0.10	1.10	0.19	0.15	0.06	96.68
AB7	7.09	0.91	0.52	1.63	0.03	2.71	0.04	0.09	1.91	0.09	0.13	0.14	96.0
AS14	6.85	1.15	0.45	1.33	0.38	2.79	0.03	0.09	1.82	0.10	0.18	0.04	97.5
AS41	6.52	1.48	0.31	1.70	0.44	2.31	0.04	0.15	1.93	0.04	0.40	0.09	95.46
AS22	6.51	1.50	0.49	1.93	0.25	2.23	0.04	0.13	1.87	0.01	0.44	0.13	96.74
AS3	6.63	1.37	0.61	1.88	0.38	2.10	0.04	0.07	1.87	0.07	0.27	0.05	97.73
AP3	6.68	1.32	0.48	2.14	0.34	2.00	0.03	0.10	1.82	0.10	0.32	0.09	95.81
AP4	6.66	1.34	0.59	1.05	0.17	2.03	0.04	0.10	1.81	0.11	0.33	0.06	93.05
AB2	6.25	1.75	0.28	1.76	0.66	1.18	0.03	0.15	1.88	0.07	0.44	0.14	91.19
AB39	6.38	1.62	0.42	1.80	0.31	2.21	0.03	0.15	1.88	0.07	0.41	0.11	96.26
AB9	6.53	1.47	0.43	1.89	0.37	2.23	0.03	0.13	1.84	0.08	0.31	0.09	97.77
AB36	6.51	1.50	0.66	2.04	0.38	1.85	0.05	0.08	0.87	0.07	0.27	0.09	98.23
AB7	6.49	1.51	0.47	1.73	0.37	2.35	0.04	0.13	1.83	0.09	0.40	0.11	91.83
AB33	6.42	1.57	0.26	1.50	0.64	2.53	0.04	0.12	1.81	0.10	0.36	0.17	97.00
AB34	6.70	1.30	0.50	1.89	0.17	2.25	0.03	0.12	1.84	0.11	0.34	0.07	96.08
AB1	6.38	1.62	0.21	1.55	0.65	1.36	0.05	0.13	1.87	0.07	0.37	0.19	97.57
AB22	6.49	1.51	0.35	1.57	0.45	2.51	0.04	0.19	1.77	0.13	0.37	0.09	96.05
AB8	6.77	1.23	0.56	1.83	0.27	2.31	0.29	0.07	1.86	0.08	0.30	0.04	97.39

*Fe³ is midpoint between maximum Fe³⁺ and minimum Fe³⁺ (after Papike et al., 1974).

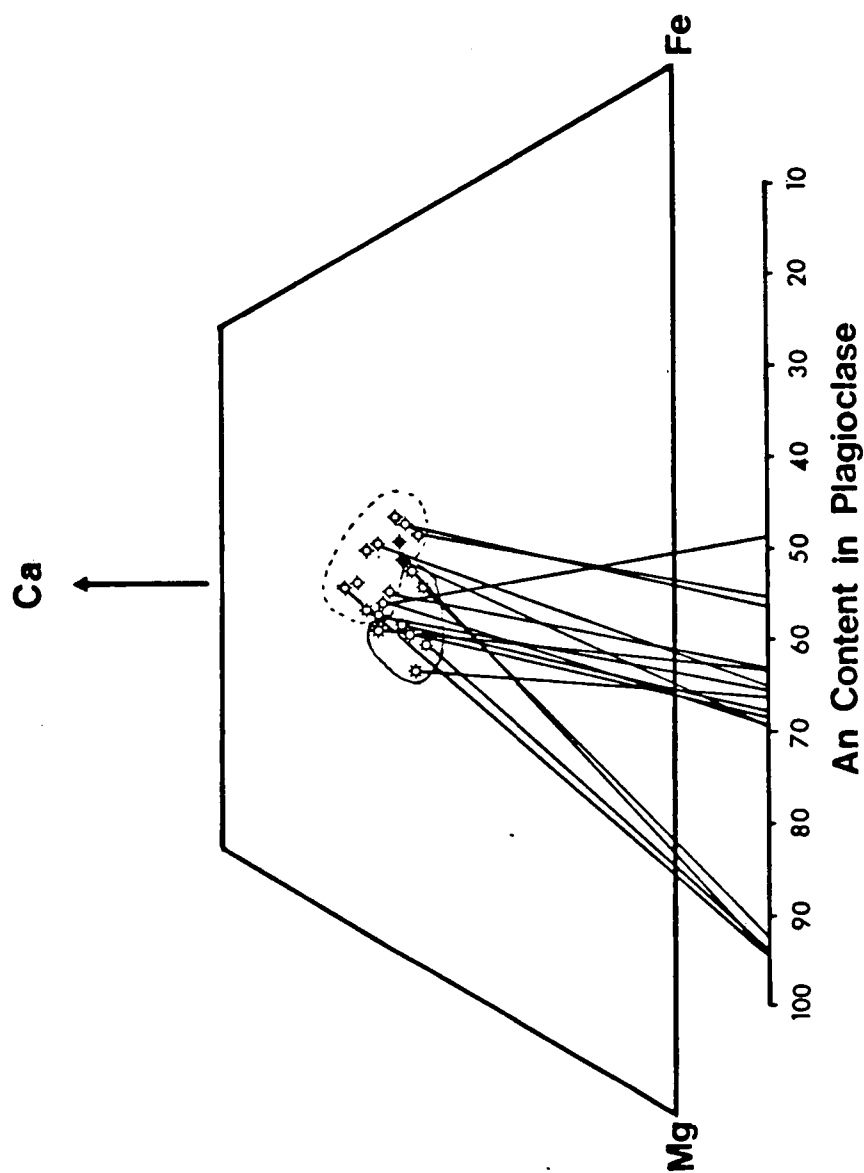


Figure 4. Ca-Mg-Fe diagram showing compositions (mole percent) of coexisting amphiboles and plagioclases from amphibolites of the Smith River allochthon. Dashed line outlines the relatively Ca-rich amphiboles from Fe-rich Philpott and Bassett quadrangles compared to those from Sanville quadrangle (full line). (✕) Sanville quadrangle; (◆) Philpott quadrangle; (⊙) Bassett quadrangle.

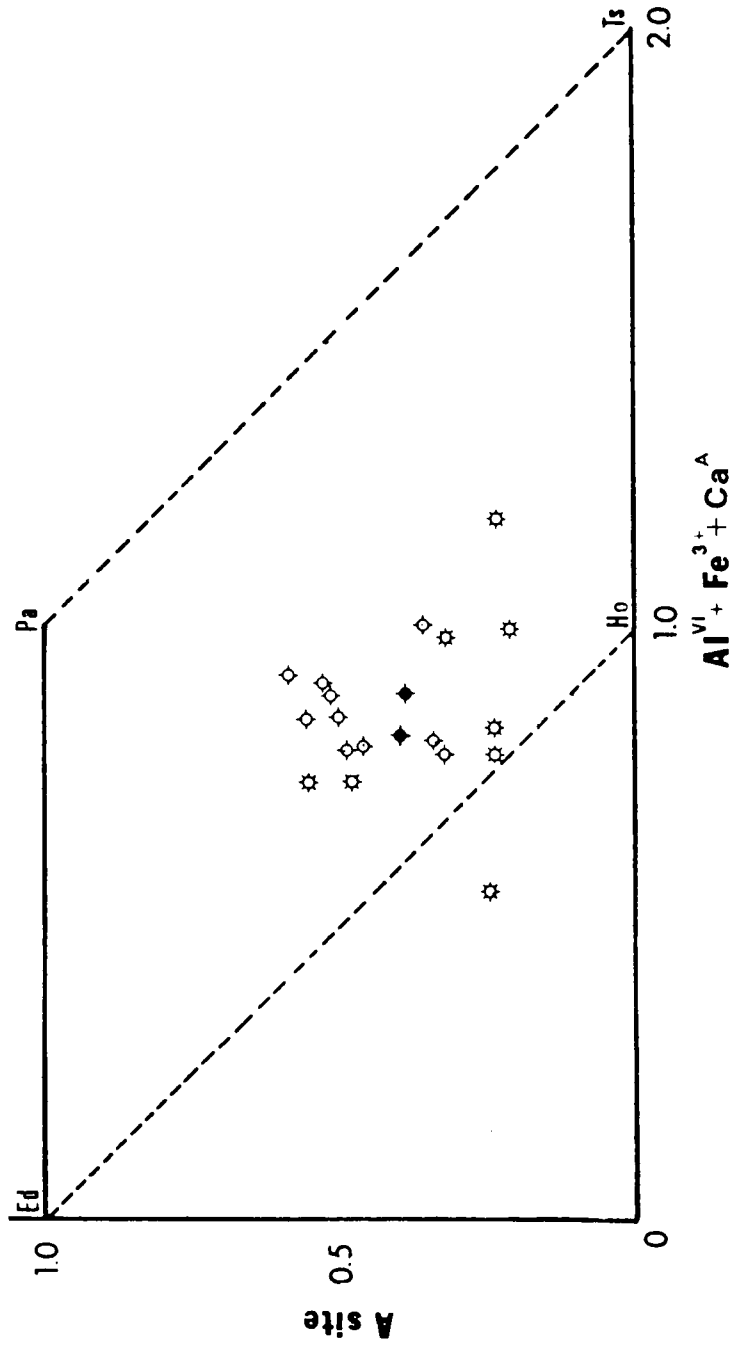


Figure 5. Plot of $Al^{VI} + Fe^{3+} + Ca^A$ versus A site occupancy of the amphiboles from the Smith River allochthon (after Pamić et al., 1972). Symbols as in Figure 4. Ed--edenite-ferroedenite; Pa--pargasite-ferropargasite; Ts--tschermakite-ferrotschermakite; Ho--common hornblende.

quadrangles being slightly richer in Ca content compared to those from the Sanville quadrangle (Figure 5). The variations may be attributed to variations in bulk rock composition, P_f , f_{O_2} , P_t , or degree of metamorphism. These factors will be discussed later.

The plagioclase feldspars can be separated into two compositional groups, $An_{55}-An_{70}$ (labradorite) and $An_{92}-An_{95}$ (anorthite). Labradorite ($An_{55}-An_{70}$) is the dominant feldspar within the study area. The large compositional range of this group may be due to the presence of primary epidote minerals which could have caused an increase of the Ca content in the coexisting plagioclase (Winkler, 1979; Wenk and Keller, 1969). In his studies at the Beaver Brook locality in Vermont, Spear (1981) was unsure if labradorite and hornblende represent a stable assemblage at the sillimanite grade. The sillimanite grade of metamorphism has apparently been attained here (discussed later), suggesting that labradorite-hornblende may be a stable assemblage at this grade of metamorphism. The anorthitic plagioclase ($An_{92}-An_{95}$) has a smaller compositional range compared to the other group. The higher anorthite content in some samples (AS7, 29, 27; AB36) may be indicative of a higher grade of metamorphism (Winkler, 1979; Engel and Engel, 1964).

None of the plagioclase grains analyzed are chemically zoned. This is consistent with a stable equilibrium

assemblage. Spear (1981a, 1980) and Wenk and Keller (1969) have reported the presence of coexisting plagioclase of different compositions in some metamorphic terrains. With the exception of one sample (AB39), all samples analyzed in the Smith River allochthon show no coexisting plagioclase compositions. Sample AB39 has coexisting plagioclase compositions of An_{49} and An_{69} which is suggestive of a Voll (An_{40} - An_{90}) miscibility gap.

The ilmenite is ferrianilmenite (hematite content is less than 10% in all cases, Appendix C). The hemo-ilmenite is richer in hematite content (approximately 28%) and the magnetite is apparently pure Fe_3O_4 with less than 1% ulvo-spinel component. Figure 6 is a TiO_2 - FeO - Fe_2O_3 ternary diagram showing the compositional plots representative of the Fe-Ti oxides.

Conditions of Metamorphism

The mineral assemblages in the amphibolites (hornblende-plagioclase-quartz-ilmenite) and overlying schist (sillimanite-muscovite-biotite-quartz-ilmenite) are consistent with an amphibolite facies of metamorphism, typically in the upper amphibolite facies, prior to granulite facies transition (Turner, 1981). This conclusion is supported by the $Na_2O + K_2O$ versus TiO_2 contents of the Smith River amphiboles (Figure 7, after Leake, 1965). Here,

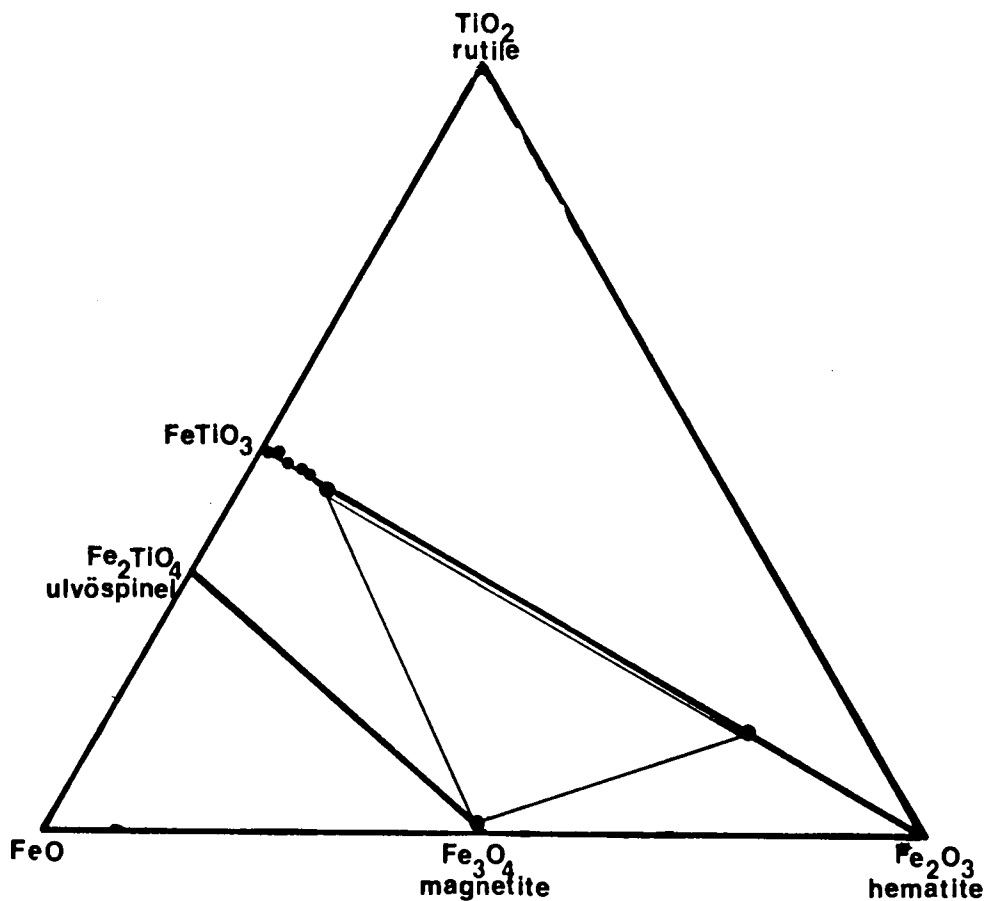


Figure 6. FeO-Fe₂O₃-TiO₂ ternary plot (in mole percent) of oxide assemblage in amphibolites of the Smith River allochthon. Sample with coexisting composition is shown with tie lines.

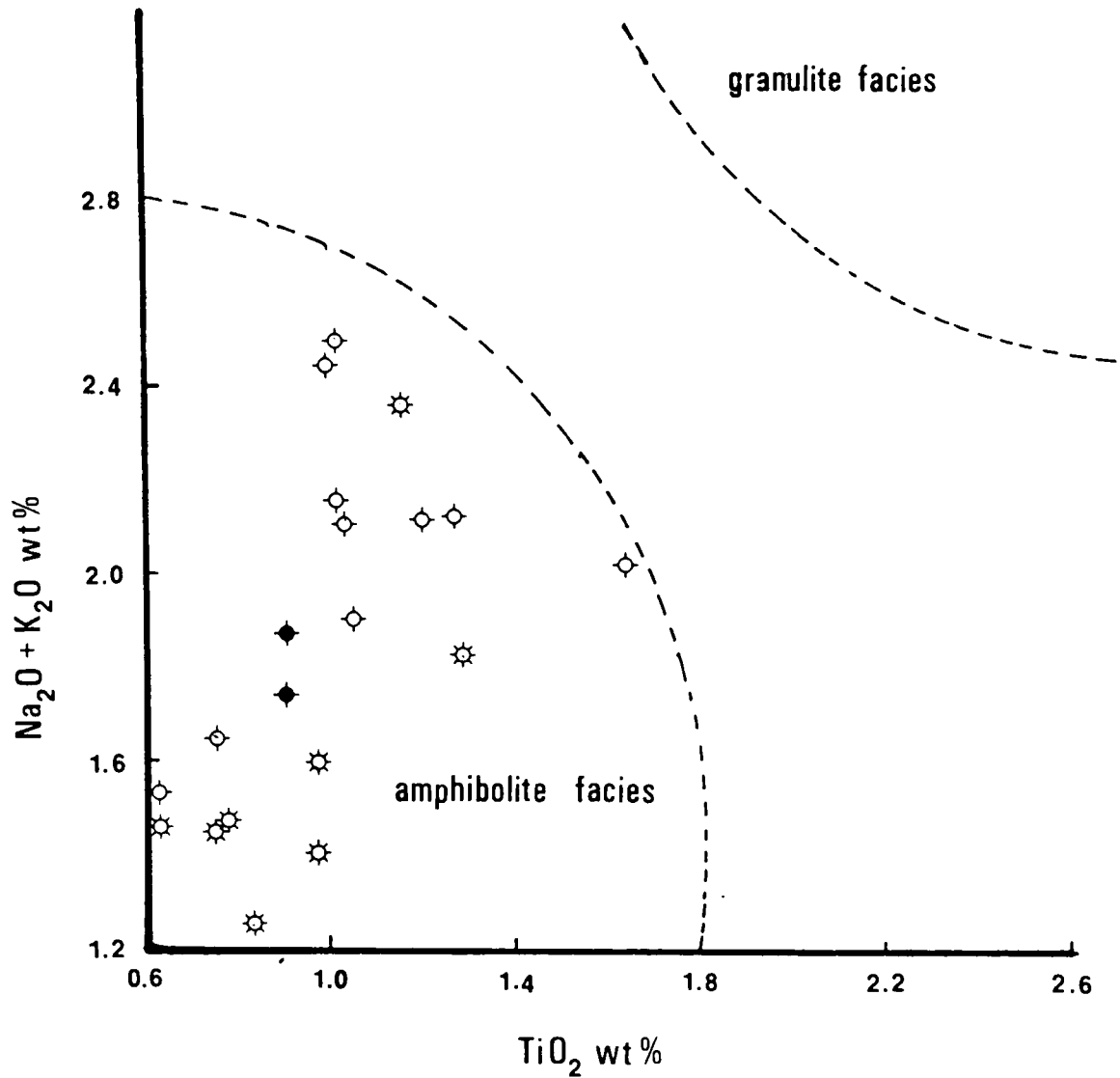


Figure 7. $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (weight percent) versus TiO_2 (weight percent) for amphiboles from the Smith River allochthon. Boundaries for amphibolite and granulite facies after Leake (1965). Symbols as in Figure 4.

it is observed that none of the amphiboles plot within the granulite field. Metamorphic grade within the amphibolite facies may be defined by the albite + tremolite $\rightleftharpoons$ edenite + 4 quartz equilibrium exchange reaction between coexisting plagioclase and hornblende (Spear, 1981a). Figure 8 shows that the X_{Ab} (plagioclase) and $X_{Na(A)}$ (hornblende) contents of the coexisting plagioclase and hornblende from the Smith River amphiboles are within the range for the sillimanite zone obtained by Spear (1981b) for coexisting plagioclase and hornblende at the Beaver Brook locality in Vermont. It is also noted that although Spear (1981b) was uncertain if labradorite and hornblende is a stable assemblage (Figure 8, question mark) at the sillimanite grade, this assemblage is apparently stable within the amphibolites in the Smith River allochthon.

Many workers have attempted to correlate metamorphic hornblende composition (e.g., Ti, Na, K, Ca, Al, Si, Fe) to define the physical conditions under which they were formed (Spear, 1981a, 1981b, 1980, 1976; Fleet and Barnett, 1978; Brown, 1978; Liou et al., 1975; Ghent, 1975; Heltz, 1972; Engel and Engel, 1964, 1962). Although these workers and others have suggested that the physical conditions of metamorphism can be correlated with compositional variations of the hornblendes, Ghent and DeVries (1972) and Bard (1970) have cautioned that such correlations are not always

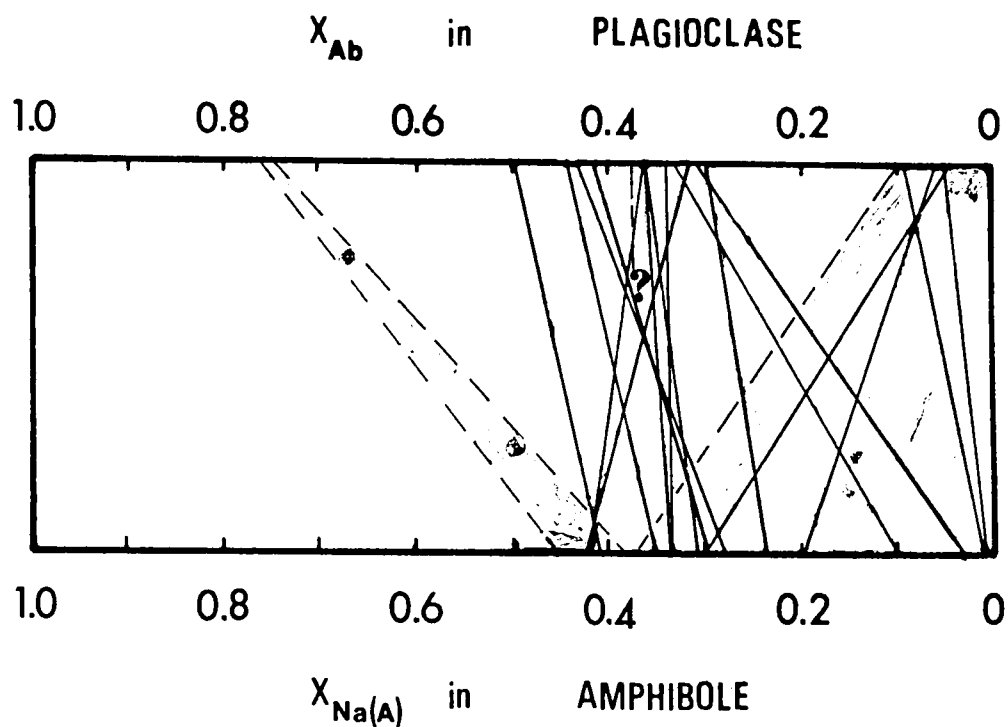


Figure 8. X_{Ab} in plagioclase versus $X_{Na(A)}$ in coexisting amphibole (Spear, 1981a) from the Smith River amphibolites. Shaded areas represent data ranges from the sillimanite zone, Beaver Brook locality, Vermont (Spear, 1981a). Question mark indicates the uncertainty by Spear (1981a) for stable coexistence of labradorite and amphibole.

consistent because of limitations placed by variations in bulk rock composition, temperature, pressure, fluid pressure and oxygen fugacity. The hornblende compositions of the Bassett Formation have apparently been affected by these factors.

Pressure under which the amphibolites from the Smith River allochthon were metamorphosed have been estimated from amphibole composition in the amphibolites and mineral assemblages present in the overlying mica schist. The amounts of Al^{IV} , Al^{VI} and Si in the amphibole structure are pressure sensitive (Raase, 1974; Fleet and Barnett, 1978) and can be correlated with the pressure of formation of the amphibole. Plots of Si versus Al^{IV} (Raase, 1974) and Al^{IV} versus Al^{VI} (Fleet and Barnett, 1978) for the Smith River amphiboles (Figure 9A and B, respectively), show that the upper pressure limit of metamorphism for the amphibolites is at least below 5 Kb, although there is a good deal of scatter. Scatter of the data points in these plots can be attributed to the uncertainty in estimation of Al partitioning between the Al^{VI} and Al^{IV} sites. Al partitioning between the two sites is dependent upon the Fe^{3+} content in the amphibole structure (Clague et al., 1981; Bard, 1970). The Fe^{3+} values assigned to the amphibole structure are recalculated values from microprobe analyses (Appendix A). Such Fe^{3+} recalculations may have imparted errors in the Al

Figure 9. Variation diagrams showing amphibole compositions in the Sanville (✱), Philpott (◆), and Bassett (◇) quadrangles amphibolites, Smith River allochthon. (A) Si vs. Al^{VI} diagram (Raase, 1974), in cation percent, with dashed line representing a 5 Kb boundary. Below this line, pressures are 5 Kb and above this line, pressures are 5 Kb. The solid line represents maximum possible Al^{VI} content in amphiboles at any given Si content (Leake, 1965). (B) Al^{VI} vs. Al^{IV} diagram, in cation percent, showing fields of unaltered igneous hornblende, low pressure metamorphic hornblende, and high pressure metamorphic hornblende (Fleet and Barnett, 1978). Compositional fields for amphiboles from the Willyama Complex, Australia (Binns, 1965) and Aracena area, Spain (Bard, 1970) are included for comparison.

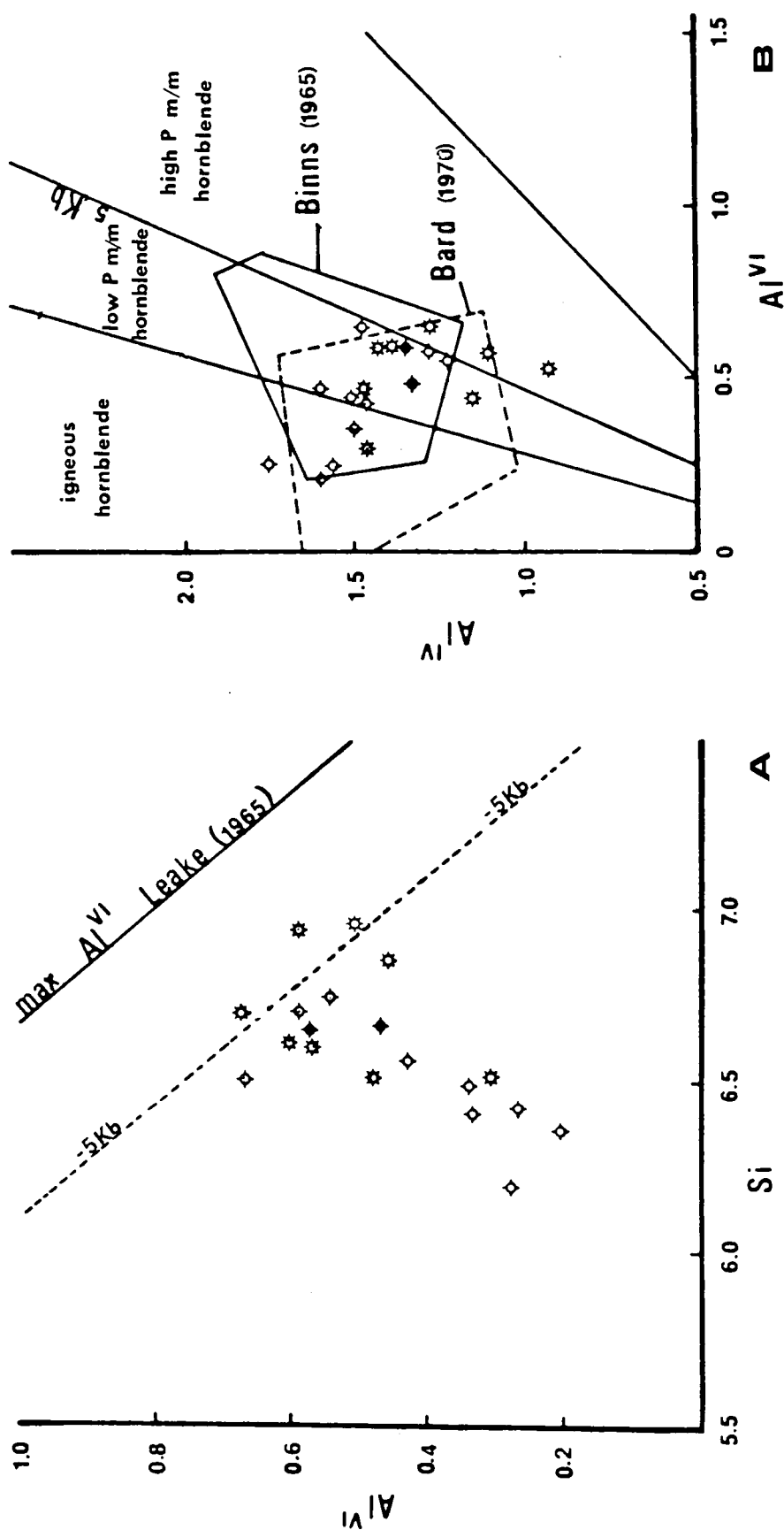


Figure 9.

partitioning, thus resulting in the scatter of the data points observed. Figure 9B also shows the amphiboles to plot within the fields for Aracena (Bard, 1970) and the Willyama Complex (Bins, 1965) for both of which the metamorphism has been inferred to be of low- to medium-pressure type.

The lower pressure limit of metamorphism of the amphibolites is not easily defined from the hornblende composition. However, Conley and Henika (1971) have reported the presence of coexisting assemblages of sillimanite-staurolite-garnet-quartz and sillimanite-staurolite-chlorotoid-quartz in the overlying mica schist. Assuming contemporaneous metamorphism of the amphibolites and overlying mica schist and using the stability relations of these assemblages (Turner, 1981), the pressure range of metamorphism of the amphibolites may be confined to within 3.5 Kb-4.5 Kb at a temperature range (discussed later) of 535°-650°C. This pressure range (3.5 Kb-4.5 Kb) is typical of medium-pressure metamorphism and is consistent with the upper 5 Kb limit derived from the hornblende compositions.

Various coexisting mineral phases have been used as geothermometers (for example, see the excellent review by Dahl, 1979). Within a rock unit, depending on the assemblage, more than one geothermometer is usually used for cross-check of the temperature estimates. Lack of certain

specific coexisting phases other than plagioclase and hornblende in the present amphibolites severely restricts the number of geothermometers that can be used. Conley and Henika (1973, 1970) and Henika (1971) have reported occurrences of clinopyroxene in few samples but this writer did not observe any coexisting clinopyroxene-hornblende in the 100 samples collected which could have been used as a geothermometer.

The most useful geothermometer for this study is the amphibole-plagioclase equilibrium: albite + tremolite $\rightleftharpoons$ edenite + 4 quartz (Spear, 1981a). This relation governs the partitioning of Na between plagioclase and the A site of coexisting hornblende. The use of this method is somewhat limited because (a) Na assigned to the A site is based upon recalculation of Fe^{3+} and (b) equilibrium conditions must be assumed. Equilibrium between plagioclase and hornblende was determined using the method of Hollander (1970) and Saxena (1969). Only those coexisting plagioclase and hornblende which displayed equilibrium or close to equilibrium conditions (based on distribution of Na, Ca, and Al between the plagioclase and hornblende) were used (Figure 10A) to determine a temperature range for metamorphism. These selected data, based on the aforementioned equilibrium give a temperature range of about 500°-725°C (Figure 10B). The temperature range can be further confined to 535°-650°C on

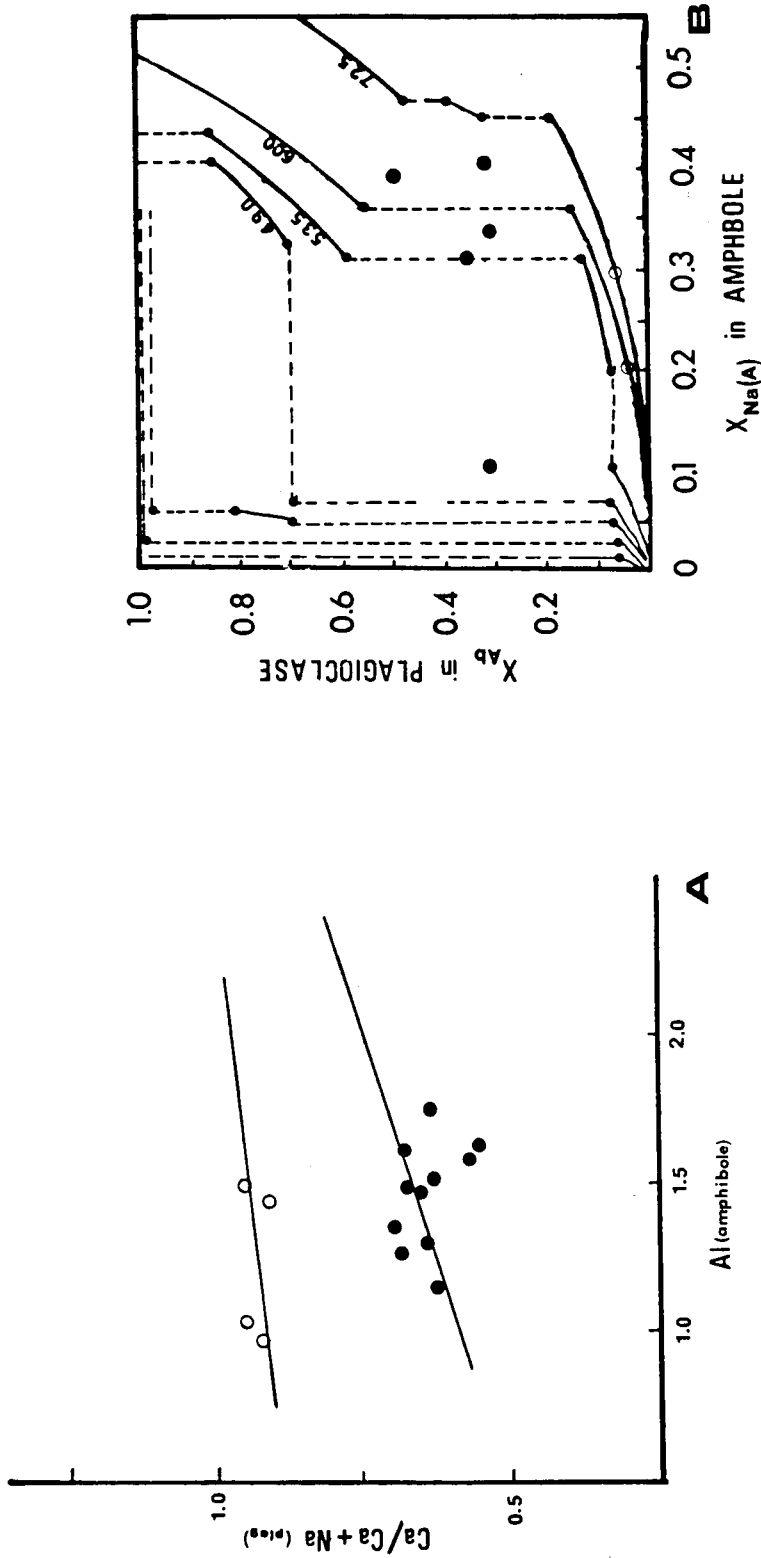


Figure 10. Distribution of Al^{IV} (amphibole) versus $\text{Ca}/(\text{Ca} + \text{Na})$ (plagioclase) for coexisting amphibole and plagioclase (Saxena, 1968) in the Smith River amphibolites (A) and $X_{\text{Na(A)}}$ in amphiboles versus X_{Ab} in plagioclase for the Smith River amphibolites with hypothetical contours as temperature determinants (B) (Spear, 1981a). (●) Plagioclase (An55-An70) coexisting with amphibole; (○) Plagioclase (An92-An95) coexisting with amphibole. Solid lines in (A) are visual estimation of best fitline.

the basis of pressure estimate (3.5 Kb-4.5 Kb) discussed earlier. This temperature range for metamorphism of the amphibolites in the Smith River allochthon seems reasonable and consistent with the available chemical data and phase assemblages present.

It has been demonstrated by various workers that P_f and f_{O_2} have a direct influence on amphibole composition (Spear, 1981b; Heltz, 1973; Oba, 1976). P_f and f_{O_2} values under which amphiboles were formed can be determined from the amphibole compositions (Spear, 1981b). Amphibole compositions (e.g., Mn, Ti, Al^{IV}) have been determined experimentally by Spear (1981b) at 700°-750°C under differing P_f and f_{O_2} conditions when buffered along the WM, QFM, and HM buffers. This experimental work enabled Spear (1981b) to empirically determine P_f and f_{O_2} conditions (from elemental compositions) under which the amphiboles were formed. A comparison between compositions of the Smith River amphiboles and those from Spear's (1981b) experimental work makes a qualitative determination of P_f and f_{O_2} for the Smith River amphibolites possible. Average values of Mn, Ti, and Al^{IV} of the Smith River amphiboles approximate the values obtained by Spear (1981b) for amphiboles buffered between the QFM and WM buffers (but closer to the QFM buffer). Assuming the QFM buffer is applicable to the Smith River amphibolites, a comparison between Spear's (1981b)

data and that of the Smith River amphiboles gives P_f of approximately 3 Kb and f_{O_2} of approximately 10^{-14} - 10^{-18} atmospheres for metamorphism of the Smith River amphibolites.

The interaction among T , f_{O_2} and bulk composition is evident by the Ti contents in the amphiboles of the Smith River amphibolites. Ti contents in amphiboles increase with metamorphic grade (Raase, 1974; Binns, 1965; Engel and Engel, 1964). Figure 11 shows a comparison of the Ti contents in the amphiboles of the Smith River amphibolites with those of various metamorphic facies compiled by Raase (1974). It is apparent that the Ti contents of the amphiboles of this study (upper amphibolite facies) are lower compared to Raase's (1974) data for the upper amphibolite facies. The lower Ti contents may be a consequence of lower temperatures or relatively Ti-impoverished bulk composition, but coexisting phases of amphibole-sphene-ilmenite suggest that the amphiboles have their maximum Ti contents in their lattice (Leake, 1965). Amphibole-sphene-ilmenite is a common mineral assemblage in the Smith River amphibolites. Thus, the lower Ti contents of these amphiboles may have been controlled by relatively high oxygen fugacities (Spear, 1977).

Spear (1981b) has shown experimentally, on the basis of sphene stability, amphibole-plagioclase-ilmenite-sphene and

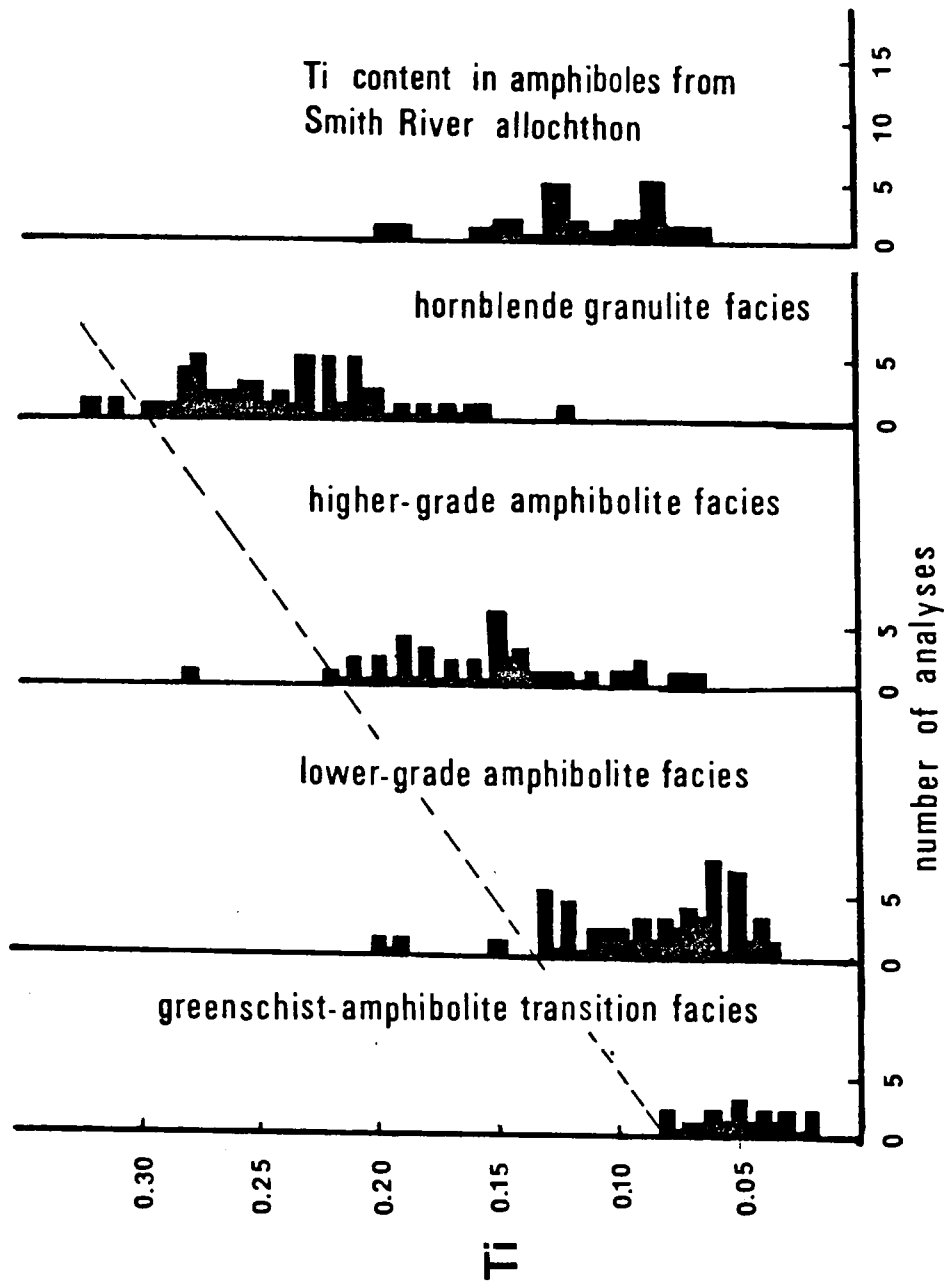


Figure 11. Histogram of Ti content, weight percent oxide, of metamorphic amphiboles versus number of analyses (Raase, 1974) compared to a histogram (far right) of Ti content, weight percent oxide, of amphiboles from the Smith River allochthon.

amphibole-plagioclase-ilmenite are stable assemblages under limiting conditions in P - T - f_{O_2} space. These are common assemblages in the Smith River amphibolites. P - T - f_{O_2} plots for the Smith River amphibolites (Figure 12A and B) show the phase assemblages present to be consistent with the previously derived conditions of metamorphism ($T = 535^{\circ}$ - 650°C ; assuming $P_f = P_T = 3.5 \text{ Kb} - 4.5 \text{ Kb}$; the amphibolites are buffered between the QFM and WM buffers as discussed previously). These relationships support the prior conclusion that the granulite facies of metamorphism was not attained in the Smith River amphibolites and the conditions of metamorphism are compatible with the stability of sphene which is an ubiquitous phase in the Smith River amphibolites.

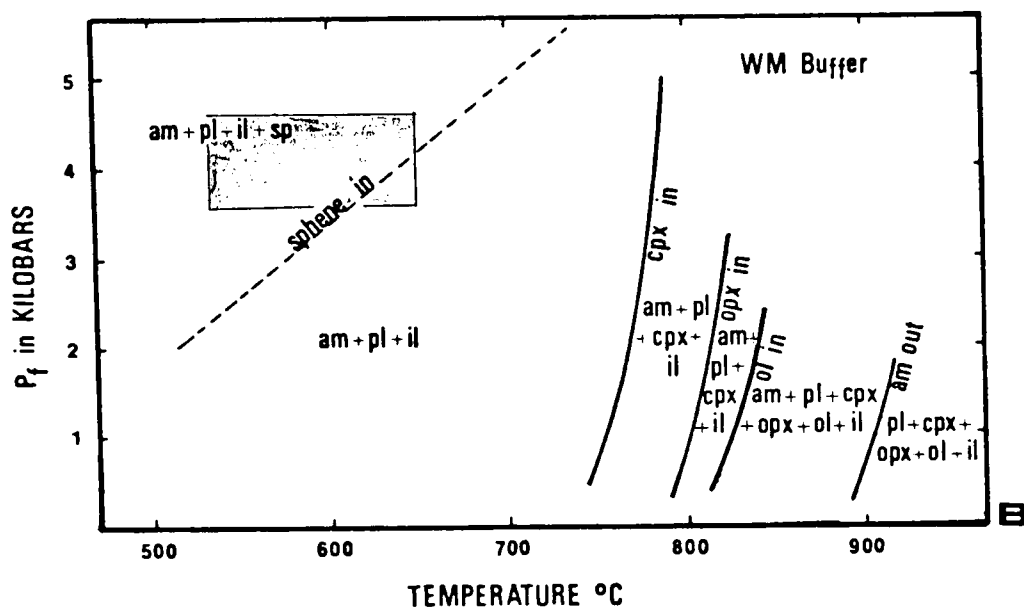
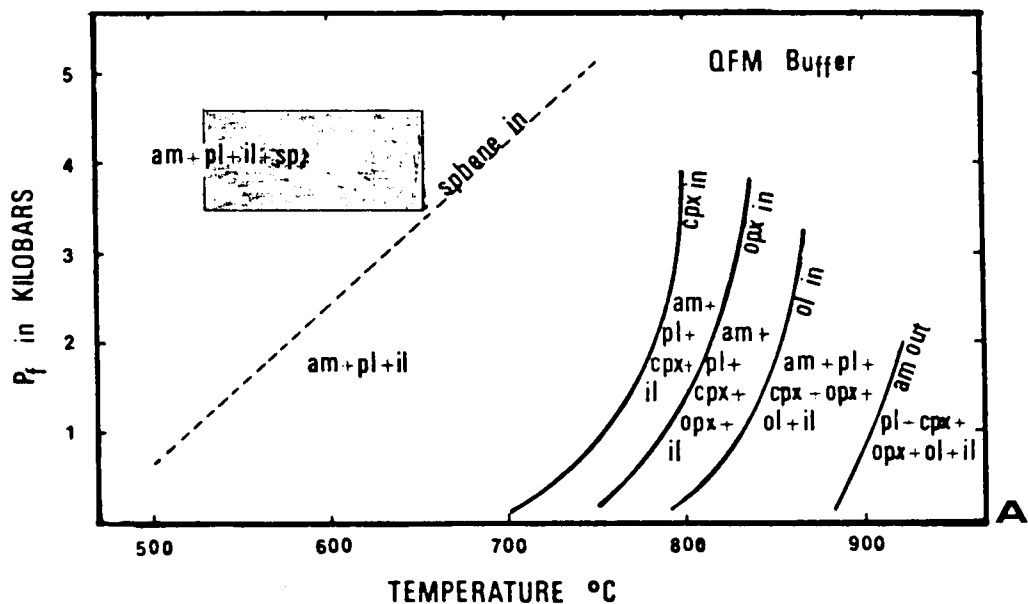


Figure 12. P_f - T relations (Spear, 1981b) for amphiboles from the Smith River allochthon (shaded area) at oxygen fugacities defined by: (A) the QFM and (B) the WM buffers.

CHAPTER 4

PETROGENESIS

Amphibolite Protolith and Chemical Affinities

Amphibolite bodies are common constituents of Precambrian medium- to high-grade metamorphic terrains. It is widely believed that the parents from which the amphibolites were derived include intrusive, extrusive, and pyroclastic basic igneous rocks. Also, Orville (1969) suggested that amphibolites may be formed by chemical diffusion between adjacent pelitic and carbonate meta-sediments.

Field relations, although helpful, do not lead to unequivocal identification of the parent rocks of the amphibolites; hence, such identification is mainly dependent upon chemical evidence. However, it is important to realize that alteration and metamorphism may not have been isochemical. Several studies have shown that significant chemical changes can occur in the parent rocks during regional metamorphism (Stephenson, 1980; Field and Elliot, 1974; Elliot, 1973; Walker et al., 1960). Other processes (submarine weathering, deuteric alteration, ocean floor and burial metamorphism) which may precede high-grade regional metamorphism may also produce chemical modification of the parental rocks (Pavlidis, 1981; Stephenson and Hensel, 1981;

Stephenson, 1980; Hart et al., 1974; Holm, 1982; Cann, 1969).

Although the problems of chemical modification of the parental rocks are recognized, chemical variation trends have been used successfully by Leake (1964) and Bard and Moine (1979) to distinguish amphibolites of basic igneous origin from those derived from sedimentary origin. Also, some trace elements (Ti, P, Zr, Y, Nb, Mg, Al, Mn, Th, Hf, Ta) appear to be relatively immobile during alteration and metamorphic processes and have been successfully applied in recent studies for determining the original chemical and tectonic affinities of the metamorphosed rocks (Winchester and Floyd, 1977, 1976; Pearce and Cann, 1973; Floyd and Winchester, 1975, 1978; Pearce et al., 1977, 1975). Major elements such as Si, Ca, Fe^{2+} , K and few trace elements which are considered to be mobile (Elliot and Harvey, 1980; Elliot, 1973) have also been used to determine original chemical and tectonic affinities of parent rocks (e.g., Sun and Nesbitt, 1978).

The interpretation of the parent rocks and the paleotectonic environment of the amphibolites in the Smith River allochthon, as discussed here, is based on their major and trace element chemistry. Chemical analyses of the 12 amphibolite samples chosen for this purpose are given in Table 3. These 12 samples encompass the different

Table 3. Whole rock chemical analyses (weight percent) of 12 representative amphibolite samples from the Smith River allochthon.

	AS22	AB1	AS27	AB33	AP3	AS7	AB27	AB25	AB36	AB8	AB39	AS13
Whole Rock Analyses (weight percent)												
SiO ₂	46.0	48.30	50.30	47.90	50.30	49.30	45.20	44.30	46.50	48.00	47.30	49.00
Al ₂ O ₃	13.40	12.40	18.10	12.40	12.00	14.30	13.10	13.20	15.00	15.20	13.30	14.90
Fe ₂ O ₃ ^a	16.60	16.50	12.40	16.00	15.80	11.10	17.18	17.20	15.10	13.20	14.70	13.40
MgO	6.56	5.59	3.39	5.32	4.76	8.69	5.99	6.02	5.36	5.82	6.45	6.71
CaO	8.83	9.94	11.80	9.29	7.59	13.10	8.92	10.30	11.50	9.43	10.20	9.76
Na ₂ O	1.65	2.04	0.84	2.48	2.04	0.87	1.24	2.35	1.08	3.09	2.33	1.81
K ₂ O	0.56	0.56	0.20	0.60	0.32	0.45	0.62	0.48	0.37	0.19	0.54	0.27
TiO ₂	2.51	3.33	2.07	3.52	3.16	0.47	3.28	3.16	2.36	2.06	2.34	1.87
P ₂ O ₅	0.15	0.15	0.30	0.31	0.33	0.04	0.22	0.26	0.27	0.23	0.19	0.22
MnO	0.22	0.20	0.32	0.21	0.21	0.18	0.23	0.22	0.25	0.16	0.19	0.17
LOI	2.93	0.54	0.39	0.47	2.16	0.77	3.47	0.77	0.62	1.08	0.54	0.77
Total	99.60	99.70	100.10	98.60	98.70	99.40	100.10	98.40	98.70	98.70	98.20	99.00
CIPW ^b Norms (weight percent)												
Q	3.04	5.18	13.75	4.00	11.12	3.16	4.92	0.00	5.68	0.02	0.65	13.40
Or	3.43	3.22	1.19	3.61	1.93	2.70	3.82	2.91	2.23	1.15	3.27	1.71
Ab	14.47	17.40	7.18	21.39	17.62	7.47	10.93	20.38	4.34	26.84	20.20	16.42
An(An)	28.50	23.27	45.46	21.34	23.12	34.28	29.52	24.66	35.76	27.76	24.83	34.03
Ne(Ne)	---	---	---	---	---	---	---	---	---	---	---	---
Di	13.11	20.29	9.50	19.49	10.99	25.51	12.50	21.50	17.19	15.39	21.16	14.02
Hy	24.95	16.59	12.88	15.75	21.59	21.15	24.44	10.15	18.07	18.57	18.54	10.03
Ol	---	---	---	---	---	---	---	6.23	---	---	---	---
Mt	7.20	6.99	5.26	6.86	6.72	4.74	6.85	7.40	6.49	5.70	6.33	6.02
Il	4.94	6.38	3.97	6.81	6.13	0.91	6.49	6.15	4.58	4.02	4.55	3.81
Ap	0.37	0.69	0.81	0.75	0.80	0.10	0.54	0.63	0.65	0.56	0.46	0.56
Niggli Values ^c												
al	18.87	17.71	27.38	18.15	19.32	10.66	18.62	17.85	21.01	21.85	18.53	21.17
c	22.65	25.85	32.51	24.77	22.25	31.17	23.09	25.37	29.34	24.69	25.89	25.26
alk	4.66	5.61	2.42	6.92	5.96	2.50	3.00	5.93	3.05	7.60	6.16	4.65
mg	0.44	0.40	0.35	0.39	0.37	0.61	0.40	0.41	0.41	0.46	0.46	0.50
Trace Elements (ppm)												
Cr	170	90	90	80	70	390	70	80	120	90	170	190
Rb	20	10	0	20	0	10	10	0	10	0	20	10
Sr	30	240	270	290	70	40	40	180	760	950	240	140
Y	20	20	50	30	50	20	40	40	20	30	20	40
Zr	110	<10	190	260	220	0	190	190	140	140	120	120
Nb	20	20	20	30	30	20	0	20	20	20	50	10
Ba	320	380	200	400	290	20	230	230	170	290	240	130
Sc	40	37	34	35	40	57	42	42	50	33	38	38
Ni	12	9	35	14	11	35	23	10	18	9	13	40
La	12	22	31	26	13	18	28	17.0	19	10	11	9
Yb	3.5	3.5	3.9	3.6	4.8	2.2	4.2	3.9	4.4	3.3	2.9	4.1
Hf	3	5	5	5	6	1	5	5	4	4	3	3
Ta	1	2	2	2	2	4	2	2	1	2	2	1
Th	0.6	1.8	4.6	2.2	1.9	20.5	1.6	0.5	0.6	1.8	0.8	0.7
La/Ta	12	11	15	13	6.5	1.8	14	8.5	19	5	5	9
Hf/Ta	3	2.5	2.5	2.5	3	1	2.5	2.5	4	2	1.5	3

^aAll Fe calculated as Fe₂O₃.^bAll norms calculated with assumed Fe²⁺/Fe³⁺ ratio of .71.^cNiggli values are: al (from Al₂O₃), c (from CaO), alk (from Na₂O + K₂O), mg = MgO/MgO + MnO + FeO.

petrologic types observed in the study area and therefore are considered to be representative of the chemical variations in the sampled amphibolite bodies.

Leake (1964) suggested that chemical variation trends using Niggli mg ($\text{MgO}/\text{FeO}+\text{MnO}+\text{MgO}$), c (CaO), al (Al_2O_3), and alk ($\text{K}_2\text{O}+\text{Na}_2\text{O}$) in suites of samples provide the best means of discriminating between amphibolites produced from a basic igneous horn and those from sedimentary rocks. Figure 13 shows that Niggli 100 mg-c-(al-alk) plots for the Smith River amphibolites closely follow an igneous trend which suggests that the parental rocks of the amphibolites is of an igneous origin. The igneous origin for the amphibolites is corroborated by plots of $\text{Al}+\text{Ti}+\text{Fe}$ versus $\text{Ca}+\text{Mg}$ and $(\text{Al}+\text{Ti}+\text{Fe})/3--\text{K}$ versus $(\text{Al}+\text{Ti}+\text{Fe})/3--\text{Na}$ which are considered by Bard and Moine (1979) as reliable discriminants among igneous and various sedimentary rock types. Plots of these values for the Smith River amphibolites (Figure 14A and B) suggest a basaltic origin for the protolith of the Smith River amphibolites.

None of the above discriminant diagrams show any positive trends towards a sedimentary origin for the amphibolites of the Smith River allochthon. The trends are indicative of an igneous origin, specifically a basalt. Also, the amphibolites are removed from the spilitic field which suggests that they may not have undergone ocean-floor

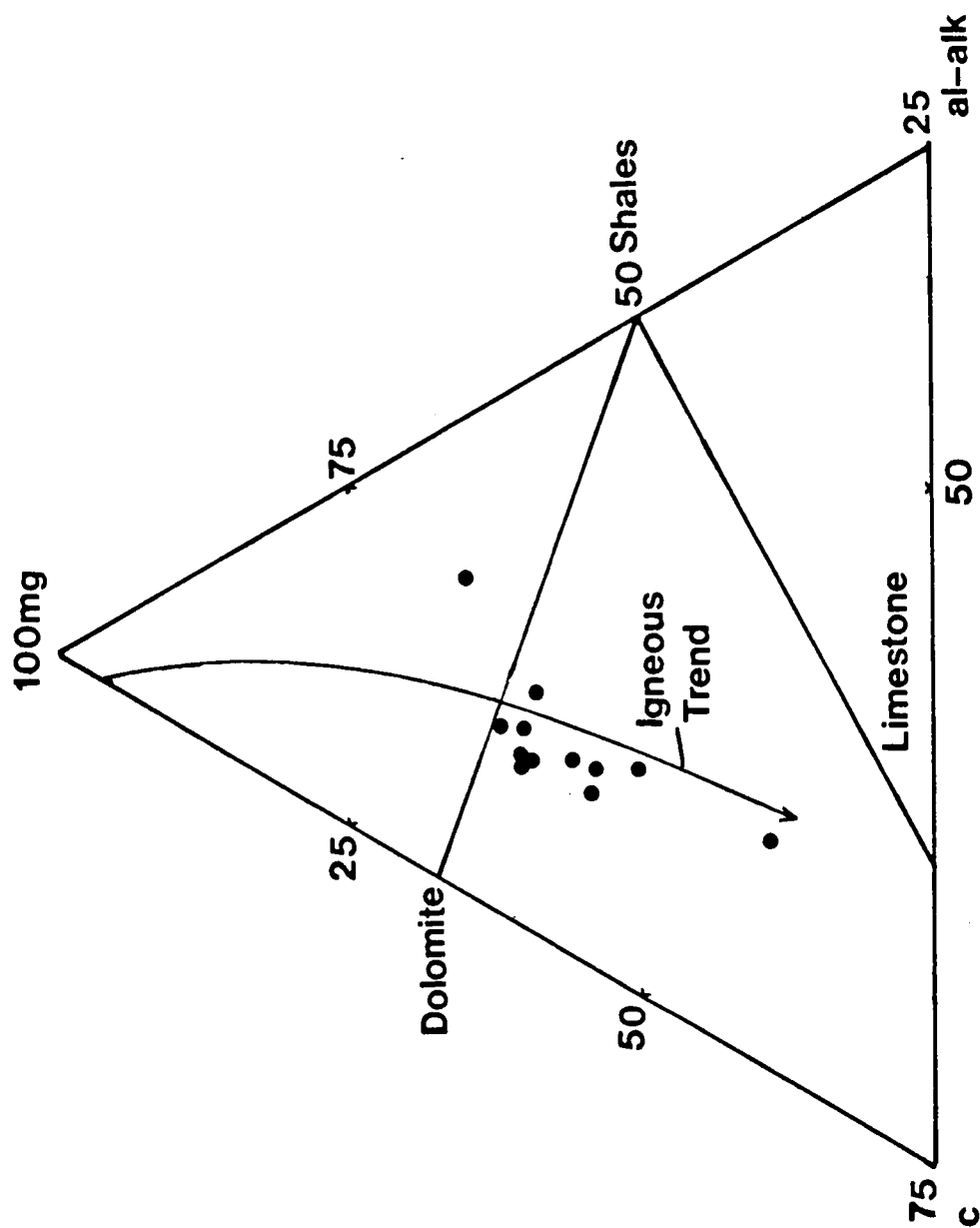


Figure 13. Niggli 100 mg-c-(al-alk) plot for the amphiboles from the Smith River allochthon compared with the trends observed for igneous rocks and pelite-carbonate mixtures (after Leake, 1964).

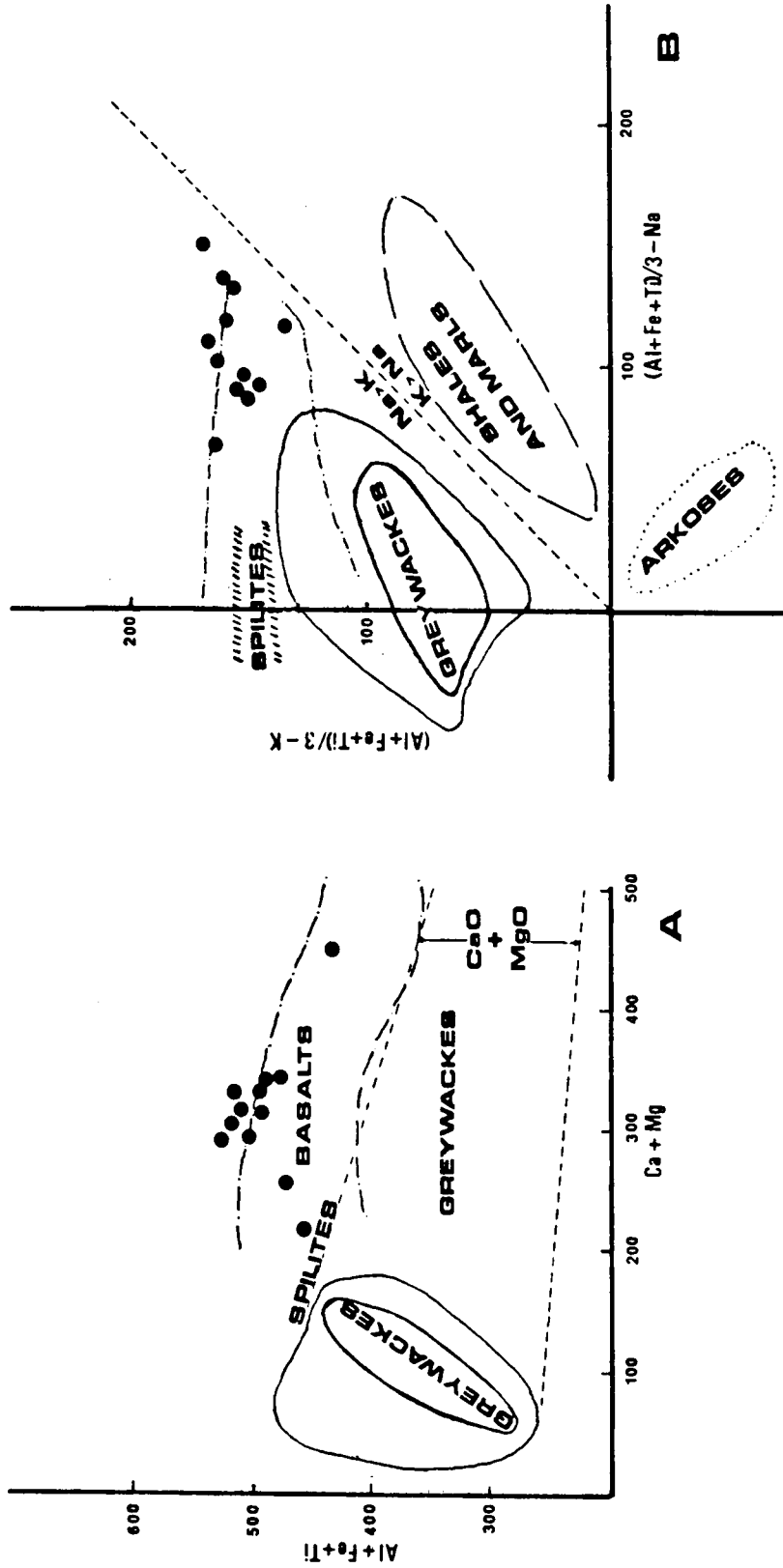


Figure 14. $Al + Fe + Ti$ versus $Ca + Mg$ and $(Al + Fe + Ti)/3 - K$ versus $(Al + Fe + Ti)/3 - Na$ discriminant diagrams (Bard and Moine, 1979) for amphibolites from the Smith River allochthon. Al , Fe , . . . etc., are the contents in millimoles of each element in 100 grams of rock.

metamorphism. The basaltic nature of the protolith is substantiated by a plot of the normative values of the amphibolites (Table 3) in the basalt tetrahedron (Figure 15). Eleven of the 12 amphibolite samples plot within the quartz tholeiite field; only one sample (AB25) plots in the olivine tholeiite field. The olivine tholeiite character of sample AB25 may be due to depletion of SiO_2 during metamorphism (discussed later); the SiO_2 content of this sample is lowest relative to the other samples with equivalent Niggli mg values. A tholeiitic character for the amphibolites from the Smith River allochthon is also suggested by the AFM plot (Figure 16).

Variation diagrams of some selected major and trace elements versus Niggli mg values of the Smith River amphibolites (Figure 17) show some elements with typical differentiation trends whereas others display effects of metasomatism. Differentiation trends with decreasing mg values are reflected by enrichment followed by decrease of Fe content, general increase in TiO_2 , Zr, Y, and decrease in Cr contents. Differentiation is also suggested by increases of P_2O_5 and Nb, although the changes are not very pronounced. These differentiation trends suggest that these elements remained relatively immobile even during high-grade metamorphism. Thus, employment of these elements in various discriminant diagrams may be regarded with some degree of

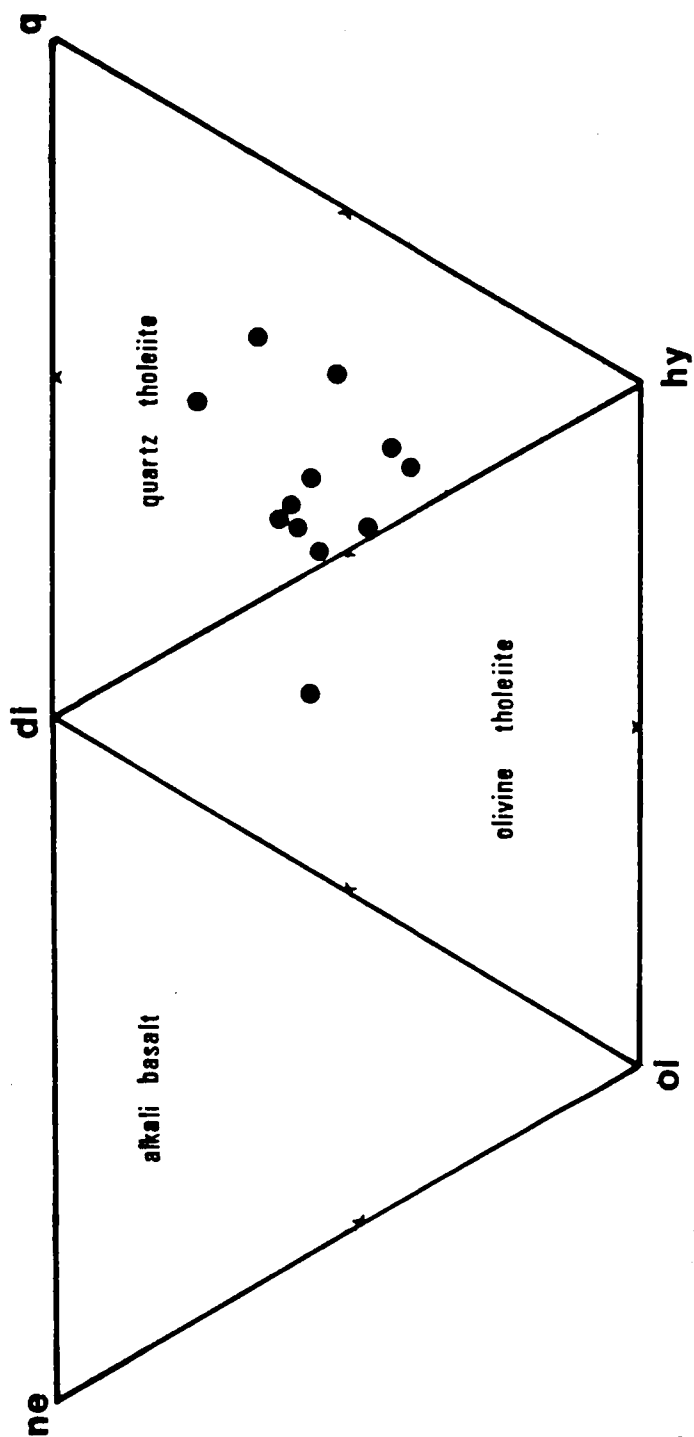


Figure 15. CIPW-normative compositions of amphibolites from the Smith River allochthon in terms of the basalt tetrahedron of Yoder and Tilley (1962).

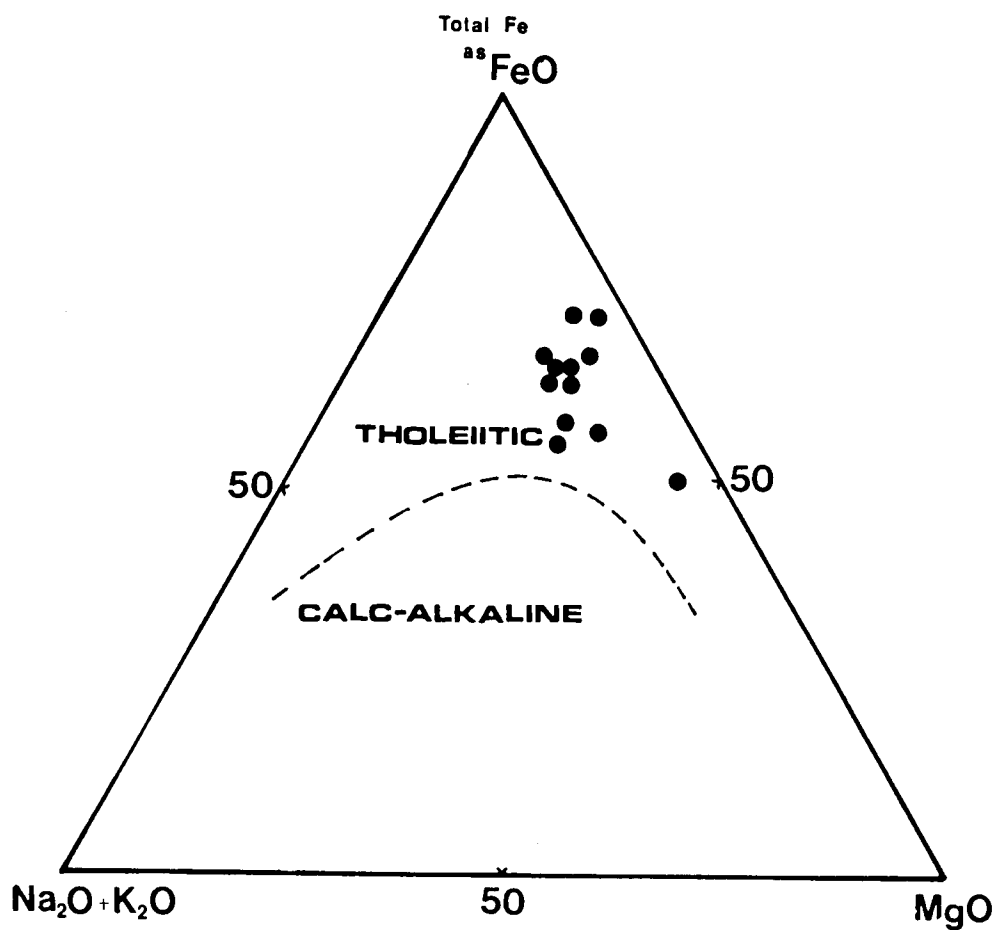


Figure 16. AFM plot of the Smith River amphibolites. Tholeiitic--calc-alkaline boundary after Irvine and Barager (1971).

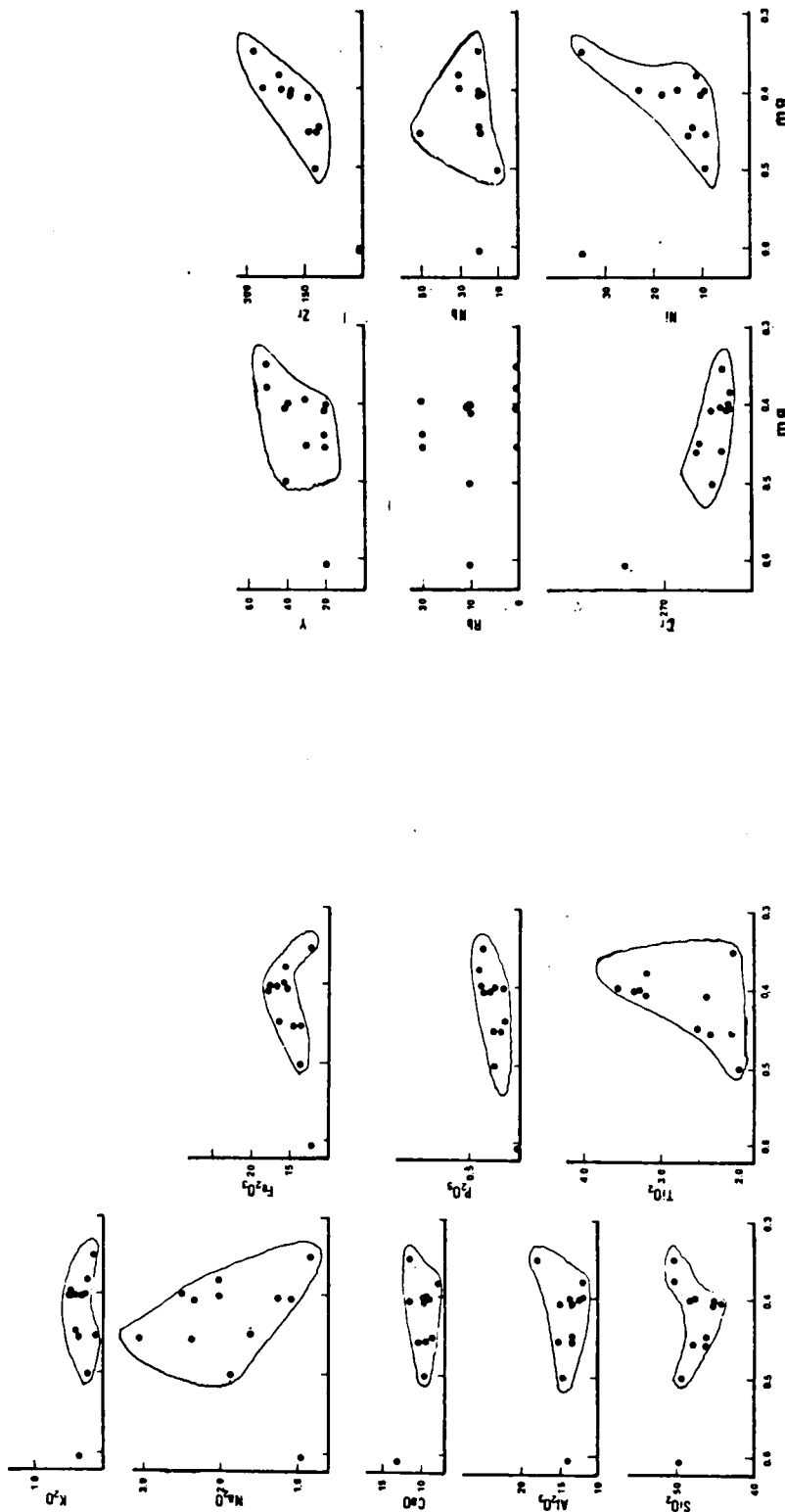


Figure 17. Selected major element oxides (weight percent) and trace elements (ppm) plotted against Niggli mg number for the Smith River amphibolites. Fe_2O_3 is total iron expressed as Fe_2O_3 . One sample (AS7) is clearly anomalous in having its very high mg value (0.61) and its chemical composition; it probably represents cumulate material.

confidence. Ni differentiation trends are anomalous because they show an increase rather than decrease with decreasing mg values. Si shows an initial decrease and then increase with decreasing mg, whereas Na_2O shows some depletion. The irregular distribution of SiO_2 , Na_2O and Rb suggest that these elements underwent some degree of metasomatism. K_2O content in the amphibolites is very low and may represent a loss of K during metamorphism.

As is evidence from Figure 17, sample AS27 is anomalous. It has a very high Niggli mg value (0.61), very low TiO_2 content (0.47) which does not plot on Figure 17, low Na_2O content (0.87), and extremely high Cr content. The high CaO/TiO_2 and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios of this sample relative to the others suggest that it may represent cumulate material rich in plagioclase. The chemical composition of this (with the exception of the high Cr content) closely resembles the amphibolites derived from metamorphosed norite in Alabama described by Stow et al. (1983). Subsequent discussions will exclude sample AS27.

Tectonic Setting

The geochemical data and appropriate discriminant diagrams discussed have so far shown the protolith of the Smith River amphibolites to be a tholeiitic basalt. This nonalkalic character of the basaltic protolith appears to be

confirmed by plots of TiO_2 versus Y/Nb and Nb/Y versus $\text{Zr/P}_2\text{O}_5$ (Floyd and Winchester, 1975). These discriminant diagrams are used to differentiate between continental and oceanic alkali basalts as opposed to continental and oceanic tholeiitic basalts. Such plots for the Smith River amphibolites are shown in Figure 18A and B. The TiO_2 versus Y/Nb plot shows the basalt to be generally a continental tholeiite in spite of some scatter of data points. According to Floyd and Winchester (1975), the Nb/Y versus $\text{Zr/P}_2\text{O}_5$ diagram is most useful for distinguishing continental and oceanic tholeiites from continental and oceanic alkali basalts. This plot clearly defines the basaltic protolith of Smith River amphibolites to be tholeiitic but with continental and/or oceanic affinities.

The range of values for the immobile elements (Ti, Sr, Y, Zr, and Nb) of the Smith River amphibolites have been compared with these values for some modern basalts and metabasalts with their tectonic settings (Figure 19, compiled by McLean et al., 1981). It is obvious from this comparison that there are considerable similarities between continental and ocean island basalts (both of which occur in an intraplate tectonic setting) and the Smith River amphibolites. This cursory comparison implies that the metabasalts of the Smith River amphibolites were most likely derived from an intraplate tectonic setting. A $\text{Ti}/100\text{-Zr-Y}+3$

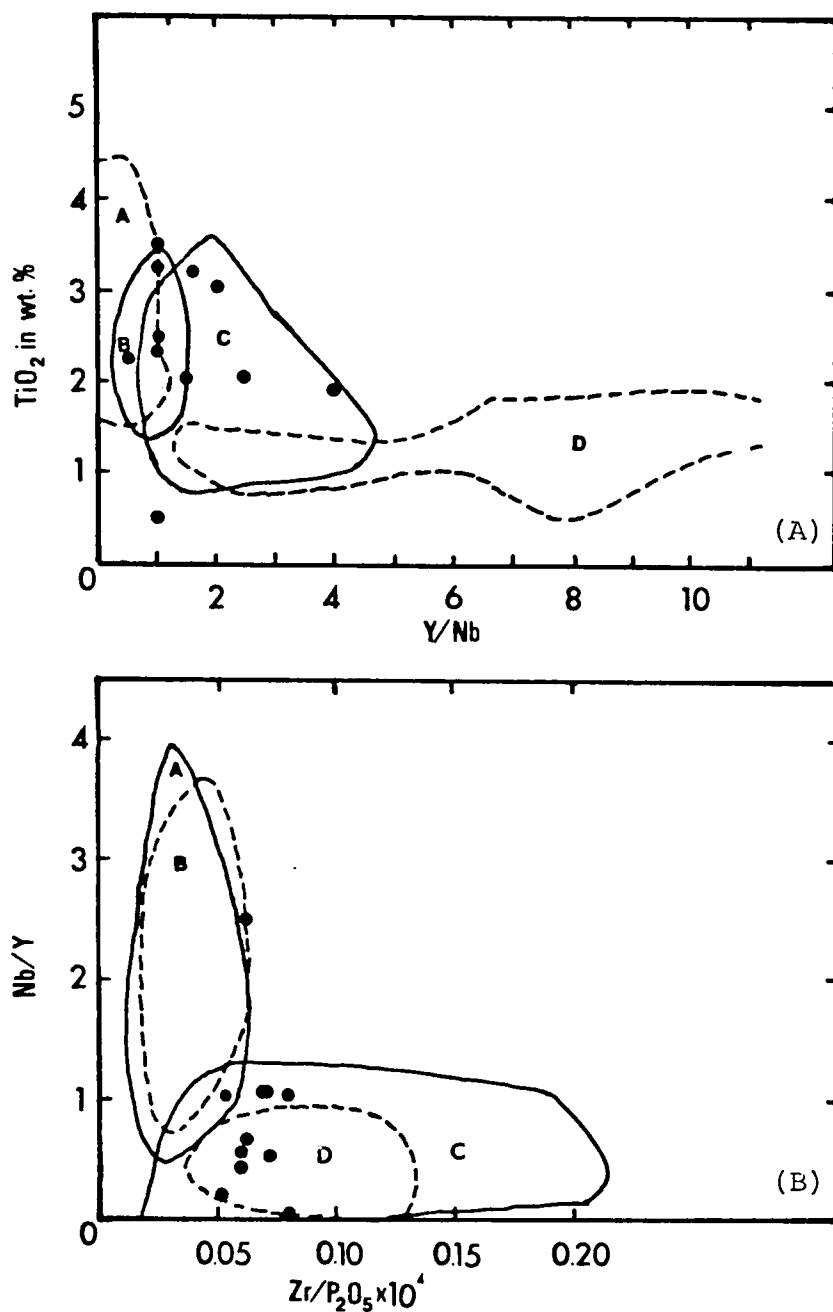


Figure 18. TiO_2 versus Y/Nb and Nb/Y versus $\text{Zr/P}_2\text{O}_5$ discriminant diagrams (after Floyd and Winchester, 1975)² for the Smith River amphibolites. Fields for both (A) and (B) are: A--oceanic alkali basalt; B--continental alkali basalt; C--continental tholeiitic basalt; D--oceanic tholeiitic basalt.

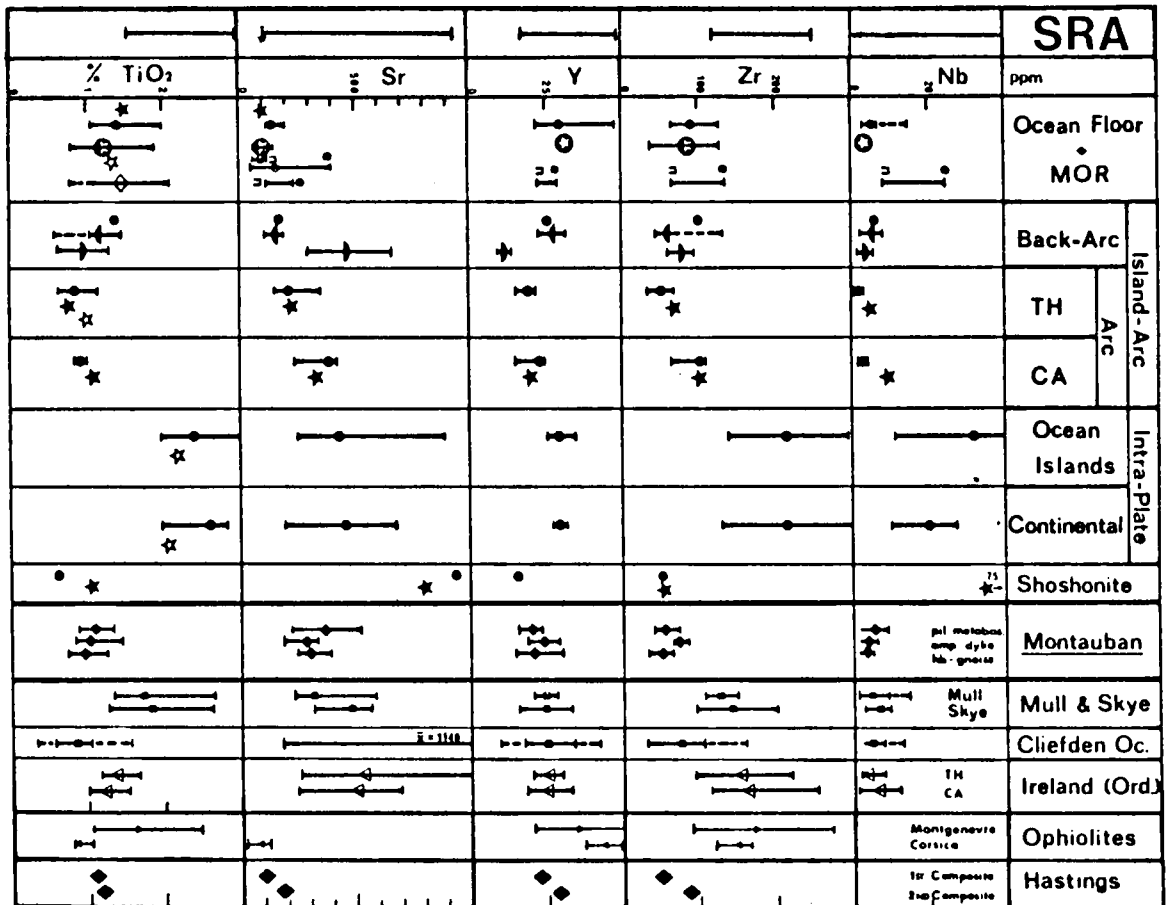


Figure 19. Comparison of abundances of trace elements in amphibolites from the Smith River allochthon (SRA) to modern basalts and to other metabasalts (adapted from McLean et al., 1981).

discriminant diagram (Pearce and Cann, 1973) for the amphibolites (Figure 20) adds credence to this conclusion. Nine of the 11 samples fall within the field defined for an intraplate tectonic setting. Two samples (AS27 and AS13) which plot within the ocean floor basalt field are anomalous in that their high quartz normative contents (13.75 and 13.40, respectively) are not typical of ocean floor basalts. Thus on the basis of trace element geochemistry, it may be stated with some degree of confidence that the protolith of the Smith River amphibolites was derived from an intraplate tectonic setting.

Of the various tectonic settings present in an intraplate environment, the basalt could have been derived from either a continental rift setting or from ocean islands. However, as pointed out earlier, CIPW normative plots have shown the basalt to be quartz normative which is typical of a continental rift setting whereas ocean island basalt is dominantly alkaline. This argument is used to justify the conclusion that the Smith River amphibolites were derived from a basalt which was generated through a continental rift system.

Generation of continental tholeiites through rift systems involves varying degrees of melting of upper-mantle peridotites followed by some combination of fractional crystallization, crustal contamination, and wall-rock

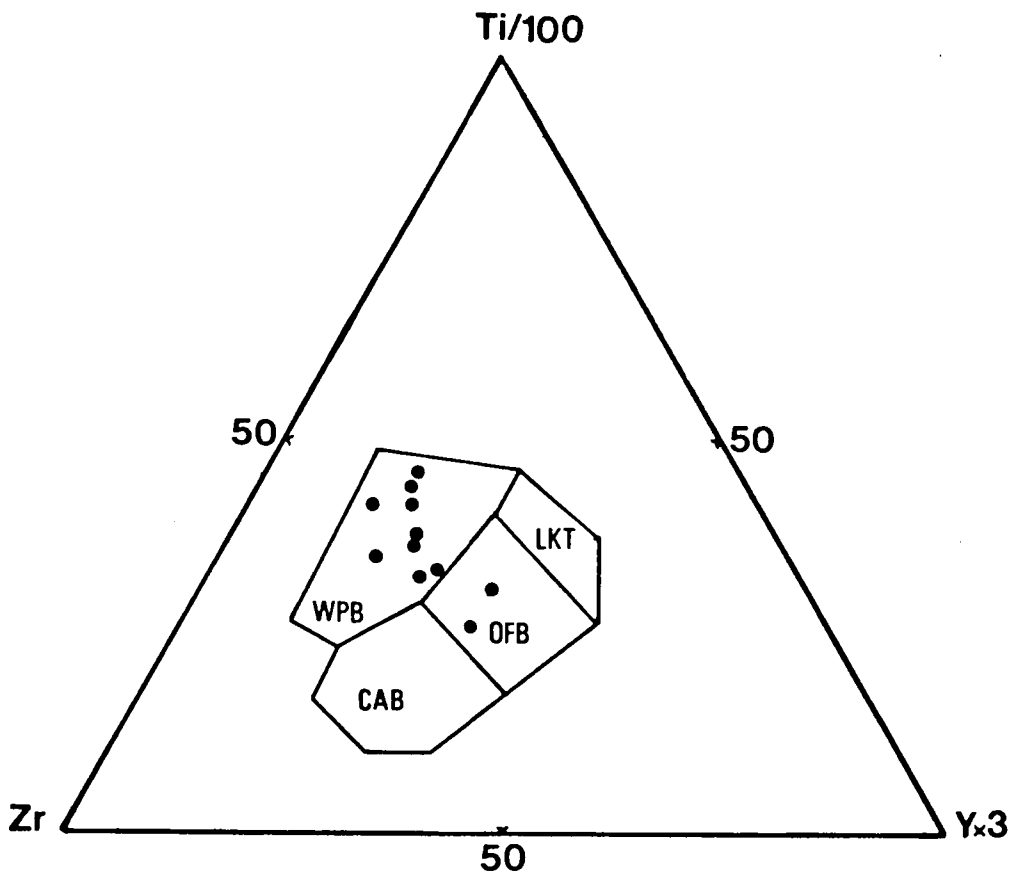


Figure 20. $Ti/100$ - Zr - $Y \times 3$ discriminant diagram (Pearce and Cann, 1973) for the Smith River amphibolites. WPB--within plate basalt; LKT--low potassium basalt; OFB--ocean floor basalts; CAB--calc-alkaline basalts.

alteration (Condie, 1982; McDougall, 1976). Compositionally, continental tholeiites are enriched in LREE elements such as K, Rb, Sr, Ba, Zr, La, Yb, compared to all other basalt types. However, because of the varying degrees of post-production processes which can occur, it is difficult to make a valid comparison between the chemical composition of the Smith River amphibolites with that of known rift basalts (e.g., the Columbia River Plateau).

Tectonic Setting and the Appalachian Orogen

If it is accepted that the protolith of the Smith River amphibolites was derived from a continental rift system, it may be possible to speculate how it related to the present understood evolution of the Southern Appalachians. Two major problems associated with the Smith River amphibolites are (1) age of the amphibolites and (2) timing of metamorphism of the amphibolites. It is almost certain that the amphibolites of the Smith River allochthon are Preordovician (Rankin, 1975; Conley and Henika, 1973; Odom and Russel, 1975). However, as suggested by Conley and Henika (1973), stratigraphic correlations suggest that the amphibolites are most likely Precambrian. Two dates have been proposed for metamorphism of the Smith River amphibolites: 1020 m.y. (Conley and Henika, 1973) and 460 m.y. (Odom and Russel, 1975); on the basis of the regional geology between the

Smith River allochthon and the Inner Piedmont (Rankin, 1975), the timing of metamorphism proposed by Odom and Russel (1975) for the amphibolites appears to be compatible with recent models for the evolution of the Appalachians.

The evolution of the Appalachian orogen has been associated with the opening and closing of a late Precambrian-early Paleozoic ocean (e.g., Hatcher and Odom, 1980; Hatcher, 1978; Rankin, 1975). A recent model for the evolution of the Appalachians (Hatcher and Odom, 1980) proposes that initial rifting of the Laurasian continent began during the early Precambrian. This initial rifting and associated rift basalts was followed by later episodes of spreading and subduction with subsequent production of volcanic and sedimentary rocks. Deformation and metamorphism of these rocks occurred as a result of the opening and closing of the late Precambrian-early Paleozoic ocean. These metavolcanic and metasedimentary rocks are present in the Blue Ridge and Inner Piedmont belts of the Southern Appalachians. It is also evident that the metavolcanic rocks of the Inner Piedmont were derived from a continental rift system, whereas the metavolcanic rocks of the Charlotte and Carolina slate belts were derived from arc systems. Timing of metamorphism of the rocks in the Blue Ridge and Inner Piedmont corresponds to the Taconic orogeny (400-500 m.y. ago), during which time the rocks which comprise

the Blue Ridge and the Inner Piedmont were thrust onto the North American craton.

Stratigraphic correlations have suggested that the amphibolites with host gneiss and schist of the Smith River allochthon are of Precambrian age. The geochemical and petrological studies of these amphibolites have suggested that the protolith was a continental tholeiite derived from a continental rift setting. Assuming that the protolith of the amphibolites were Precambrian in age, the evidence from this study is compatible with the idea that the basalts were probably derived from a rift system associated with the initial (?) rifting of the Laurasian continent. The comparable ages between the timing of metamorphism of the Blue Ridge and the Inner Piedmont and that proposed by Odom and Russel (1975) for the Smith River amphibolites suggest contemporaneous association.

The metavolcanic rocks of the Inner Piedmont and the amphibolites of the Smith River allochthon appear to be similar because (1) both are Precambrian in age, (2) both may have been derived from continental rift settings, and (3) both may have undergone contemporaneous metamorphism. It is possible that the Smith River allochthon was initially a part of the Inner Piedmont but became allochthonous through some later orogenic event.

Summary

1. Amphibole-plagioclase-quartz-ilmenite-sphene is the most common phase assemblage in the amphibolites of the Sanville, Philpott and Bassett quadrangles.

2. Electron microprobe analysis has shown (1) the amphiboles are all calcic and chemically similar with some minor variations, (2) the dominant plagioclase coexisting with the amphiboles is labradorite ($An_{55}-An_{70}$) and (3) the ilmenite is ferrianylmenite.

3. Chemical composition of the amphiboles and coexisting plagioclase in the amphibolites and mineral phase assemblages present in the overlying schist suggest regional metamorphic conditions to be: $T = 535^{\circ}-650^{\circ}C$, $P_t = 3.5 \text{ Kb}-4.5 \text{ Kb}$, $P_f \approx 3 \text{ Kb}$ and $f_{O_2} \approx 10^{-14}-10^{-18}$ atmospheres.

4. Bulk chemistry of the amphibolites and appropriate discriminant diagrams have suggested that the protolith of the amphibolites is a tholeiitic basalt and, was probably derived from a continental rift system.

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APPENDICES

APPENDIX A

Calculation of Amphibole Structural Formula

The Fe^{3+} content in the amphiboles may be critical in calculating the hornblende cation site occupancy. Deer et al. (1963), Leake (1965), and Robinson et al. (1971) have determined that the cation proportions expressed as cations per formula unit (computed on the anhydrous basis of 23 oxygens) in which all FeO (from microprobe data) equals Fe^{2+} , is satisfactory for amphiboles with low total Fe (e.g., tremolite). On the other hand, amphiboles which are considerably richer in total Fe have substantial amounts of Fe^{3+} , especially if the amphiboles are metamorphic in origin. The high Fe^{3+} contents of Fe bearing phases (e.g., Fe-Ti oxides) which coexist with the Smith River amphiboles suggest that the amphiboles have significant amounts of Fe^{3+} .

There is no unique method of recalculating Fe^{3+} and Fe^{2+} from the total Fe obtained by microprobe analyses. Various methods have been suggested (Stout, 1972; Heltz, 1973; Ernst, 1974; Brady, 1974; Papike et al., 1974; Leake, 1978), but none without certain assumptions and therefore entirely satisfactory. In the present study, two methods were used to recalculate Fe^{3+} and Fe^{2+} for the general amphibole formula $\text{AX}_2\text{Y}_5^{\text{VI}}\text{Z}_8^{\text{IV}}\text{O}_{22}(\text{OH})$, and the other by Papike et al. (1974). Recalculations of a set of representative amphibole analyses by the two methods are presented in

Table A-1 and Table A-2, respectively. It can be seen that Fe^{3+} values by Leake's (1978) method approximately corresponds to the maximum possible Fe^{3+} values by the method of Papike et al. (1974).

Brown (1976) suggested that microprobe analyses for amphiboles with Al^{IV} approximately 1.0 or greater should be calculated to have a Fe_2O_3 value somewhat less than half the maximum Fe_2O_3 . The relationship between Al^{IV} and Fe^{3+} is the result of substitution of Fe^{3+} in the Y site. This substitution leads to an excess of positive charge which may be balanced wither by Al^{3+} occupying the Z site or by Na^+ replacing Ca^{2+} in the X site (Binns, 1965). Binns (1965) concluded that at higher grades of metamorphism, charge balance (when Si is replaced by Al in the Z site) is maintained by alkali cations entering the A site, whereas at lower grades, the charge balance is maintained by Al entering the Y site. Hietanen (1974) observed that the ratio of A site occupancy to Al^{IV} is higher in low-medium pressure amphiboles than in high pressure amphiboles and suggests that the Fe_2O_3 content is approximately between the maximum and minimum Fe_2O_3 values.

The Smith River amphiboles appear to have been affected by low to medium pressure metamorphism, and their Al^{IV} contents are significantly higher than 1.0 (Tables A-1 and A-2). Therefore, their Fe^{3+} contents are likely to be

Table A-1. Representative microprobe analyses of amphiboles with recalculated cation distribution (after Leake, 1978).

	AS29	AS14	AS13	AS27	AS41	AS3	AS7	AS22	AF4	AP3	AB33	AB22	AB34	AB1	AB9	AB8	AB36	AB7	AB2	AB30
SiO ₂	43.4 (2)	46.8 (3)	45.5 (3)	44.5 (4)	43.7 (1)	45.9 (3)	47.2 (4)	42.8 (3)	42.9 (4)	43.9 (4)	43.4 (4)	43.7 (4)	44.5 (3)	43.0 (1)	43.9 (1)	45.6 (4)	43.9 (3)	40.9 (5)	39.0 (2)	42.0 (1)
TiO ₂	0.90 (2)	0.86 (8)	0.93 (2)	1.13 (10)	1.26 (6)	0.64 (9)	0.79 (2)	1.16 (23)	0.88 (1)	0.91 (10)	1.11 (3)	1.59 (2)	1.12 (10)	1.15 (0)	1.14 (6)	0.46 (8)	0.76 (22)	1.05 (4)	1.3 (1)	1.24 (2)
Al ₂ O ₃	1 (1)	2.9 (4)	11.2 (2)	9.40 (10)	9.98 (20)	10.8 (3)	8.97 (40)	11.2 (3)	10.5 (1)	9.90 (50)	11.3 (1)	10.2 (1)	10.5 (1)	10.6 (1)	10.8 (1)	10.7 (6)	11.8 (2)	10.6 (3)	10.8 (1)	11.6 (1)
Cr ₂ O ₃	-	n.d.	0.17 (13)	n.d.	0.05 (2)	n.d.	0.14 (2)	0.07 (2)	0.04 (3)	0.21 (10)	0.03 (2)	0.04 (2)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.04 (3)
FeO	14.7 (1)	9.5 (3)	9.57 (41)	12.9 (2)	11.9 (2)	13.6 (6)	12.7 (2)	14.3 (4)	12.6 (0)	14.8 (2)	9.2 (1)	9.6 (1)	12.3 (5)	11.3 (3)	12.6 (4)	14.1 (2)	15.3 (4)	11.4 (1)	11.89 (14)	12.4 (4)
Fe ₂ O ₃	9.3 (1)	5.2 (3)	5.97 (41)	6.1 (2)	5.4 (2)	5.9 (6)	1.1 (2)	3.5 (4)	4.8 (0)	5.5 (2)	8.4 (1)	7.1 (1)	4.6 (5)	7.1 (3)	6.0 (4)	2.9 (2)	4.5 (4)	4.5 (1)	6.80 (14)	5.4 (4)
MnO	0.36 (2)	0.25 (3)	0.20 (5)	0.25 (4)	0.27 (4)	0.33 (5)	0.27 (5)	0.27 (1)	0.28 (4)	0.18 (2)	0.27 (4)	0.34 (5)	0.18 (2)	0.38 (3)	0.24 (5)	0.21 (2)	0.42 (1)	0.27 (2)	0.24 (2)	0.24 (3)
MgO	9.3 (1)	12.7 (3)	11.0 (1)	9.20 (10)	10.8 (1)	11.8 (1)	12.0 (1)	11.6 (1)	10.9 (0)	11.1 (1)	11.1 (1)	10.9 (1)	11.5 (1)	11.7 (1)	11.5 (1)	11.7 (1)	11.7 (2)	10.79 (1)	10.9 (0)	11.5 (1)
CaO	10.6 (1)	11.6 (3)	10.7 (3)	10.5 (2)	11.8 (1)	11.8 (1)	12.0 (1)	11.6 (1)	10.9 (0)	11.1 (1)	11.1 (1)	10.9 (1)	11.5 (1)	11.7 (1)	11.5 (1)	11.7 (1)	11.7 (2)	10.79 (1)	10.9 (0)	11.5 (1)
Mg ₂ O	1.1 (1)	0.99 (5)	1.20 (4)	1.01 (0)	1.50 (10)	1.16 (4)	0.80 (6)	1.70 (10)	1.45 (1)	1.48 (17)	1.61 (4)	1.60 (5)	1.6 (1)	1.6 (1)	1.7 (1)	1.4 (1)	1.15 (3)	1.58 (3)	1.6 (1)	1.7 (1)
K ₂ O	0.1 (1)	0.30 (0)	0.31 (3)	0.55 (4)	0.43 (2)	0.24 (2)	0.80 (2)	0.68 (4)	0.32 (3)	0.45 (4)	0.88 (3)	0.46 (2)	0.35 (1)	1.00 (3)	0.45 (1)	0.24 (4)	0.47 (4)	0.56 (2)	0.68 (3)	0.58 (3)
Sum	98.23	98.1	97.15	95.54	97.09	99.97	96.87	97.18	94.47	97.22	97.57	96.73	96.75	98.82	98.31	97.79	98.5	91.95	92.31	96.70

Cations on the basis of 23 oxygens	
Si	6.338
Ti	0.101
Al ^{IV}	1.673
Al ^{VI}	0.421
Cr	-
Fe ²⁺	1.141
Fe ³⁺	1.280
Mn	0.044
Mg	2.028
Ca	1.859
Mg	0.361
Na	-
K	0.080
Total	15.106

Si	6.338	6.774	6.676	6.760	6.532	6.667	6.968	6.517	6.628	6.459	6.504	6.688	6.371	6.503	6.789	6.524	6.460	6.189	6.335
Ti	0.101	0.052	0.106	0.130	0.144	0.069	0.088	0.129	0.101	0.103	0.124	0.178	0.125	0.120	0.127	0.077	0.083	0.120	0.154
Al ^{IV}	1.673	1.226	1.324	1.248	1.468	1.333	1.032	1.484	1.372	1.377	1.541	1.496	1.312	1.628	1.497	1.211	1.497	1.540	1.780
Al ^{VI}	0.421	0.463	0.601	0.440	0.293	0.544	0.528	0.478	0.543	0.386	0.435	0.293	0.536	0.216	0.386	0.544	0.588	0.430	0.192
Cr	-	-	0.018	-	0.006	-	0.016	0.009	0.003	0.009	0.003	0.005	-	-	-	-	-	-	0.006
Fe ²⁺	1.141	1.149	1.227	1.620	1.491	1.648	1.562	1.773	1.757	1.864	1.144	1.202	1.543	1.401	1.567	1.755	1.905	1.490	1.573
Fe ³⁺	1.280	0.557	0.653	0.700	0.611	0.412	0.117	0.390	0.534	0.621	0.935	0.800	0.520	0.797	0.666	0.140	0.504	0.590	0.820
Mn	0.044	0.035	0.236	0.030	0.036	0.041	0.034	0.034	0.037	0.033	0.033	0.042	0.027	0.048	0.030	0.012	0.053	0.040	0.024
Mg	2.028	2.714	2.402	1.980	2.408	2.074	2.461	2.194	2.017	2.002	2.386	2.378	2.251	2.437	2.304	2.257	1.892	2.330	2.155
Ca	1.859	1.810	1.487	1.700	1.887	1.839	1.902	1.835	1.803	1.794	1.765	1.739	1.839	1.857	1.827	1.872	1.865	1.820	1.860
Mg	0.361	0.140	0.313	0.300	0.113	0.162	0.098	0.145	0.197	0.206	0.234	0.261	0.206	0.143	0.173	0.128	0.135	0.180	0.140
Na	-	0.040	0.023	-	0.114	0.161	0.136	0.353	0.331	0.211	0.327	0.202	0.211	0.303	0.306	0.266	0.197	0.300	0.356
K	0.080	0.020	0.052	0.100	0.090	0.044	0.150	0.128	0.081	0.086	0.116	0.038	0.072	0.128	0.095	0.054	0.094	0.120	0.108
Total	15.106	15.100	15.308	15.108	15.398	14.994	15.304	15.489	15.267	15.310	15.401	15.138	15.330	15.479	15.371	15.320	15.420	15.383	15.510

Fe₂O₃ calculated.

Units in () represent one standard deviation of replicate analyses in terms of least units cited.

n.d. = not detected.

between the maximum and minimum possible values, and an average of the maximum and minimum possible values, as is calculated by the method of Papike et al. (1974), is considered to be the most realistic representation of Fe^{3+} in these amphiboles. The Fe^{3+} and Fe^{2+} values used in the present study have been calculated by this method.

Each electron microprobe analysis given in Tables A-1 and A-2 is the average of a representative amphibole grain in the corresponding amphibolite sample. Each analysis given in Table A-3 is the average of several grains which were analyzed for the sample; the amphibole compositions used in the text (see Table 2, p. 27) correspond to the averages given in this table.

Table A-3. Electron microprobe analyses of amphiboles (sample average) with recalculation of cation distribution (after Papike et al., 1974).

	AS19	AS14	AS13	AS27	AS41	AS3	AS22	AP4	AP3	AB33	AB22	AB34	AB1	AB9	AB8	AB36	AB7	AB2	AB39
SiO ₂	44.4 (14) ^b	46.9 (2)	45.5 (3)	44.7 (4)	42.7 (9)	44.5 (8)	47.8 (10)	43.0 (6)	42.9 (1)	43.5 (9)	42.7 (7)	43.0 (5)	44.4 (3)	43.7 (2)	43.6 (4)	40.9 (5)	39.0 (5)	42.0 (1)	
TiO ₂	0.79 (15)	0.83 (5)	0.93 (2)	0.96 (6)	1.28 (3)	0.62 (6)	0.77 (5)	1.15 (5)	0.88 (1)	0.83 (10)	1.05 (5)	1.65 (5)	1.06 (5)	1.18 (3)	1.15 (4)	0.61 (5)	0.75 (8)	1.27 (3)	1.28 (5)
Al ₂ O ₃	11.7 (6)	9.35 (35)	11.2 (2)	9.28 (17)	9.90 (14)	11.3 (8)	8.16 (60)	11.1 (3)	10.6 (1)	9.94 (39)	10.3 (1)	10.4 (2)	10.6 (2)	10.3 (2)	10.8 (1)	10.2 (5)	10.6 (3)	10.8 (2)	11.6 (1)
Cr ₂ O ₃	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
FeO	14.2 (10)	10.9 (2)	12.2 (1)	15.8 (5)	13.3 (1)	15.1 (3)	13.1 (2)	15.2 (2)	15.8 (3)	16.7 (5)	11.9 (6)	12.5 (3)	15.0 (1)	12.4 (2)	15.1 (1)	14.8 (2)	16.3 (4)	13.0 (1)	13.1 (2)
Fe ₂ O ₃	5.5 (10)	3.5 (2)	3.5 (1)	1.6 (5)	3.8 (1)	3.4 (3)	0.3 (2)	2.2 (2)	2.3 (3)	3.0 (5)	5.7 (6)	4.0 (1)	3.5 (1)	5.8 (2)	3.2 (1)	2.4 (2)	3.4 (4)	3.1 (1)	3.5 (1)
MnO	0.32 (6)	0.27 (1)	0.20 (2)	0.26 (1)	0.29 (4)	0.29 (2)	0.28 (1)	0.28 (1)	0.28 (1)	0.19 (1)	0.29 (2)	0.32 (2)	0.20 (2)	0.40 (2)	0.26 (2)	0.23 (2)	0.40 (2)	0.27 (2)	0.24 (1)
MgO	9.68 (50)	12.9 (2)	11.0 (1)	9.12 (5)	10.6 (3)	9.44 (28)	12.2 (6)	9.88 (5)	8.76 (10)	8.76 (14)	11.3 (1)	11.2 (3)	10.0 (1)	11.0 (1)	9.99 (10)	10.4 (4)	8.31 (13)	9.93 (10)	9.13 (4)
CaO	10.4 (2)	11.7 (1)	10.7 (3)	11.0 (2)	11.8 (1)	11.7 (1)	12.0 (1)	11.5 (1)	10.9 (1)	11.1 (1)	11.2 (1)	10.9 (1)	11.4 (1)	11.6 (1)	11.5 (1)	11.7 (1)	11.7 (1)	10.8 (1)	10.9 (1)
Mg ₂ O	1.06 (3)	0.98 (6)	1.20 (4)	0.95 (6)	1.44 (7)	1.18 (5)	0.76 (5)	1.72 (3)	1.45 (5)	1.40 (1)	1.58 (5)	1.49 (4)	1.55 (5)	1.52 (4)	1.69 (3)	1.31 (7)	1.58 (5)	1.63 (3)	1.61 (7)
K ₂ O	0.42 (7)	0.26 (2)	0.31 (3)	0.48 (7)	0.45 (2)	0.24 (1)	0.21 (9)	0.66 (1)	0.32 (1)	0.46 (2)	0.89 (3)	0.48 (3)	0.34 (1)	0.99 (1)	0.45 (1)	0.22 (2)	0.56 (2)	0.68 (1)	0.58 (1)
Sum	98.47	97.59	96.73	94.15	95.56	97.77	96.08	96.69	94.19	95.88	96.91	96.14	96.05	97.59	97.85	97.48	98.2	91.79	96.19
Cations on the basis of 23 oxygens																			
Si	6.55	6.85	6.72	6.90	6.52	6.63	7.09	6.51	6.66	6.68	6.43	6.49	6.70	6.38	6.53	6.77	6.51	6.49	6.38
Ti	0.09	0.09	0.10	0.11	0.15	0.07	0.09	0.13	0.10	0.10	0.12	0.19	0.12	0.13	0.13	0.07	0.08	0.13	0.15
Al ^{IV}	1.45	1.25	1.28	1.10	1.48	1.37	0.91	1.50	1.34	1.32	1.57	1.51	1.30	1.62	1.47	1.23	1.50	1.51	1.62
Al ^{VI}	0.59	0.45	0.67	0.59	0.31	0.60	0.52	0.49	0.59	0.48	0.25	0.35	0.59	0.21	0.43	0.56	0.66	0.47	0.47
Cr	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Fe ²⁺	1.75	1.33	1.51	2.04	1.70	1.88	1.63	1.93	2.05	2.14	1.50	1.57	1.89	1.55	1.89	1.84	2.04	1.73	1.80
Fe ³⁺	0.61	0.38	0.39	0.18	0.44	0.38	0.03	0.25	0.27	0.34	0.65	0.45	0.17	0.66	0.37	0.27	0.38	0.37	0.40
Mn	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.02	0.04	0.04	0.03	0.05	0.03	0.03	0.05	0.04	0.03
Mg	2.13	2.79	2.42	2.10	2.41	2.09	2.71	2.33	2.03	2.00	2.53	2.51	2.25	2.46	2.23	2.31	1.85	2.35	2.18
Ca	1.65	1.82	1.70	1.81	1.93	1.87	1.91	1.87	1.81	1.82	1.81	1.76	1.84	1.87	1.84	1.86	1.87	1.83	1.88
Na	0.15	0.10	0.19	0.14	0.04	0.07	0.09	0.07	0.11	0.10	0.10	0.13	0.11	0.07	0.08	0.08	0.07	0.09	0.06
Na ⁺	0.15	0.18	0.15	0.13	0.39	0.27	0.13	0.44	0.33	0.32	0.36	0.37	0.34	0.37	0.41	0.30	0.37	0.40	0.41
K	0.08	0.05	0.06	0.09	0.09	0.05	0.13	0.13	0.06	0.09	0.17	0.09	0.07	0.19	0.09	0.04	0.09	0.11	0.11
Total	15.24	15.22	15.22	15.24	15.5	15.32	15.28	15.59	15.39	15.41	15.5	15.46	15.41	15.56	15.5	15.36	15.37	15.52	15.52
Fe ³⁺ _{max}	0.64	0.38	0.38	0.18	0.48	0.38	0.04	0.25	0.27	0.34	0.65	0.45	0.17	0.66	0.37	0.27	0.38	0.37	0.40
Fe ³⁺ _{min}	1.28	0.83	0.80	0.80	1.51	1.51	0.00	0.35	0.00	0.35	2.99	0.57	0.00	3.89	0.97	0.31	1.52	0.79	3.75
Fe ³⁺ _{av}	5.46	3.50	3.49	1.59	3.82	3.39	0.27	2.20	2.30	2.96	5.73	3.96	1.49	5.81	3.24	2.39	3.37	3.08	5.44

^aFeO and Fe₂O₃ (average of maximum and minimum values) calculated from FeO (total).
 Units in () represent one standard deviation of replicate analyses in terms of least units cited.
 * = not calculated.

APPENDIX B

Table B-1. Representative microprobe analyses of plagioclase coexisting with amphiboles.^a

	AS29	AS14	AS13	AS27	AS41	AS7	AP4	AB33	AB34	AB1	AB9	AB36	AB7	AB2	AB39
SiO ₂	46.8 (1) ^b	54.2 (2)	55.1 (2)	44.5 (1)	54.8 (1)	45.5 (1)	53.6 (2)	57.96 (1)	56.3 (3)	57.5 (0)	54.9 (1)	45.4 (0)	55.4 (0)	56.4 (0)	54.1 (5)
Al ₂ O ₃	33.3 (2)	27.6 (1)	27.4 (1)	34.1 (1)	27.4 (0)	33.7 (1)	27.6 (0)	24.9 (4)	27.5 (1)	25.6 (1)	27.2 (1)	33.7 (0)	27.8 (0)	27.1 (0)	27.5 (1)
CaO	17.3 (1)	10.0 (1)	10.4 (1)	18.3 (1)	10.1 (1)	17.4 (1)	10.7 (2)	7.8 (1)	9.7 (1)	7.6 (1)	10.1 (1)	17.5 (1)	9.2 (1)	9.0 (0)	10.7 (0)
Na ₂ O	1.63 (3)	5.6 (1)	5.27 (1)	1.08 (1)	5.3 (2)	1.27 (0)	5.2 (2)	6.6 (1)	6.0 (1)	6.7 (2)	5.7 (1)	1.05 (1)	5.9 (1)	5.7 (1)	5.3 (1)
K ₂ O	n.d. ^c	0.04 (0)	n.d.	0.02 (0)	0.04 (2)	n.d.	0.02 (0)	0.04 (1)	0.04 (3)	0.16 (1)	0.04 (2)	n.d.	0.06 (1)	0.04 (2)	0.04 (1)
Sum	99.03	97.44	98.17	98.00	97.64	97.87	97.12	97.30	99.54	97.56	97.94	97.65	98.36	98.24	97.64
Cations on the basis of 8 oxygens															
Si	2.167	2.500	2.519	2.092	2.516	2.128	2.483	2.625	2.532	2.625	2.519	2.124	2.562	2.563	2.490
Al	1.818	1.499	1.475	1.886	1.485	1.859	1.509	1.380	1.459	1.379	1.461	1.864	1.490	1.452	1.494
Ca	0.855	0.494	0.509	0.922	0.497	0.873	0.532	0.380	0.469	0.368	0.496	0.882	0.499	0.439	0.528
Na	0.143	0.500	0.466	0.098	0.467	0.124	0.465	0.581	0.825	0.595	0.503	0.095	0.517	0.498	0.469
K	—	0.001	—	0.001	0.001	—	0.001	0.001	0.001	0.004	0.001	—	0.002	0.001	0.001
Total	4.983	4.994	4.969	4.999	4.966	4.984	4.990	4.968	5.286	4.971	4.980	4.965	5.070	4.963	4.982
An	92.13	66.31	68.49	94.89	67.86	93.29	69.53	56.56	64.03	55.01	66.29	94.86	63.08	63.78	69.00
Ab	7.87	33.54	31.43	5.05	31.99	6.64	30.40	43.27	35.84	44.30	33.57	5.14	36.54	36.05	30.72
Or	—	0.15	—	0.06	0.15	—	0.07	0.17	0.13	0.69	0.14	—	0.38	0.17	0.28

^aTables A-1 and A-2.

^bUnits in () represent one standard deviation of replicate analyses in terms of least units cited.

^cn.d. = not detected.

APPENDIX C

Table C-1. Representative microprobe analyses of Fe-Ti oxides.

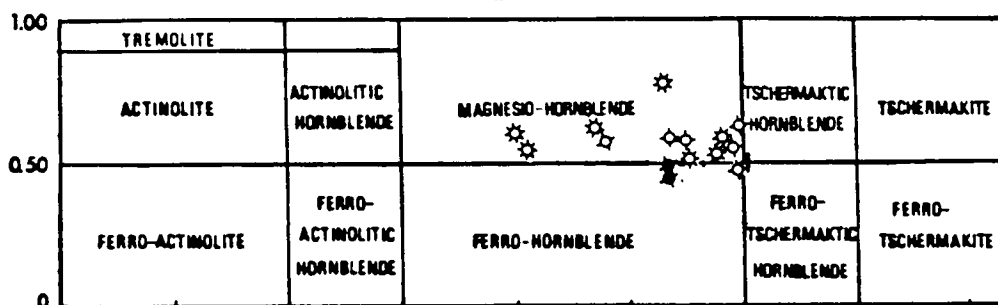
	AS14		AB33		AS36	
	Ilm	Ilm	Mag	Hem	Ilm	Ilm
TiO ₂	52.1 (3) ^a	47.5 (4)	0.19(2)	13.9 (5)	50.7 (3)	
Al ₂ O ₃	0.05(1)	0.08(1)	0.11(1)	0.12(0)	0.09(0)	
Cr ₂ O ₃	0.03(2)	1.00(10)	0.13(2)	0.14(1)	0.01(0)	
FeO	43.7 (2)	50.3 (2)	90.6 (3)	75.3 (4)	44.7 (4)	
MnO	1.86(4)	0.02(1)	0.01(0)	0.27(1)	1.71(9)	
MgO	0.45(2)	0.27(1)	0.05(1)	0.06(0)	0.25(0)	
Sum	98.19	99.17	91.09	89.79	97.46	
Recalculation on magnetite-ulvospinel/hematite-ilmenite basis (Carmichael, 1967)						
Fe ₂ O ₃	-0.55	8.40	66.78	69.94	1.42	
FeO	44.17	42.71	30.47	12.25	43.46	
Total	98.06	99.95	97.74	96.66	97.62	
Magnetite	--	--	97.74	--	--	
Ulvospinel	--	--	0.56	--	--	
Hematite	--	--	--	28.28	--	
Ilmenite	100.43	90.82	--	--	98.47	

^aUnits in () represent one standard deviation of replicate analyses in terms of least units cited.

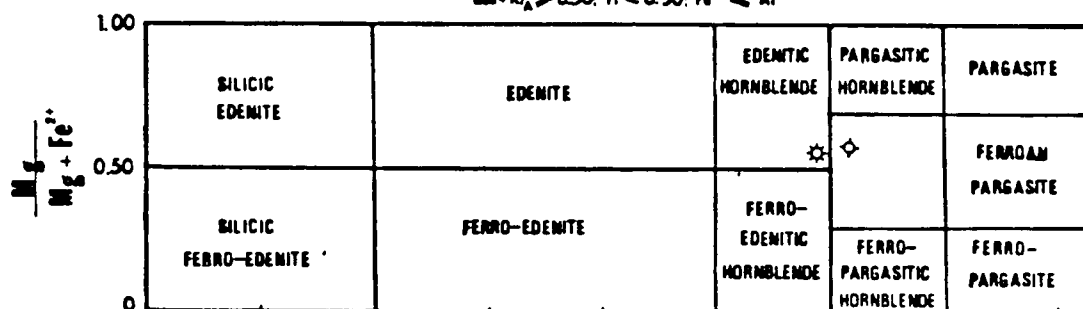
APPENDIX D

CALCIC AMPHIBOLES; $(Ca+Na)_A > 1.34; Na_A < 0.67$

$(Mg+K)_A < 0.50; Ti < 0.50$



$(Mg+K)_A > 0.50; Ti < 0.50; Fe^{3+} < Al^{IV}$



$(Mg+K)_A > 0.50; Ti < 0.50; Fe^{3+} > Al^{IV}$

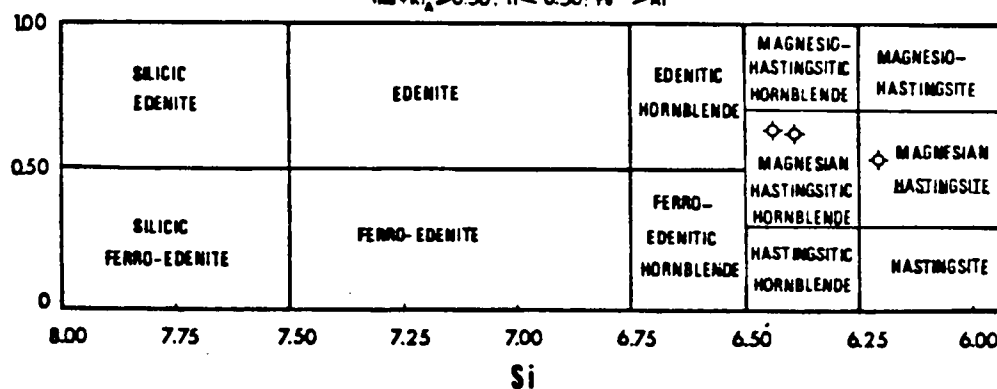


Figure D-1. Nomenclature of Smith River allochthon amphiboles (after Leake, 1978). Amphibole from Sanville quadrangle; Amphibole from Bassett quadrangle; Amphibole from Philpott quadrangle.

Table D-1. Correspondence between field and lab numbers of samples plus sample location map.

Field No.	Lab No.	Field No.	Lab No.	Field No.	Lab No.
3A1	AS1	1I2	AS30	B27	AB11
DA2	AS2	1I3	AS31	B26	AB39
3B3	AS3	2I1	AS32	B4	AB12
2C12	AS4	2J4	AS33	B59	AB13
2C11	AS5	2J1a	AS34	B58	AB14
2D4	AS6	2J2	AS35	B57	AB15
4C2	AS7	4I1	AS36	B56	AB16
3D4	AS8	4J1	AS37	B32	AB17
2E4	AS9	4J2	AS38	B55	AB18
2F4c	AS10	3J3	AS39	B52	AB19
1F1	AS11	5K1	AS40	B51	AB20
2F1	AS12	5K3a	AS41	B30	AB21
2F13	AS13	P10	AP1	B54	AB22
2G1	AS14	P11	AP2	B32	AB23
2G17	AS15	P12	AP3	B34	AB24
2G15	AS16	P14	AP4	B33	AB25
2G13	AS17	P13	AP5	B36	AB26
2G12	AS18	P8	AP6	B37	AB27
3G10	AS19	P9	AP7	B38	AB28
3G16	AS20	B18	AB1	B39	AB29
5F6	AS21	B19	AB2	B40	AB30
4F2	AS22	B20	AB3	B41	AB31
3G4	AS23	B3	AB4	B48	AB32
5G1	AS24	B21	AB5	B49	AB33
4G3	AS25	B25	AB6	B50	AB34
4G5	AS26	B22	AB7	B42	AB35
3H1D	AS27	B4	AB8	B43	AB36
3H1	AS28	B29	AB9	B44	AB37
2H5	AS29	B28	AB10	B45	AB38

VITA

Jaikisan Achaibar was born in Georgetown, Guyana, on June 5, 1955. He attended high school in Guyana before entering the City College of New York, August, 1975. He received a Bachelor of Science degree in Geology in August, 1979. In Winter of 1981, he entered The University of Tennessee, Knoxville. He received a Master of Science degree in Geology in June 1983.