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AN ABSTRACT OF THE THESIS OF William Robert McCulloch for
the Master of Science in Geology presented June 10, 1988

Title: Metasomatism Between Amphibolite and Metaultramafic
Rocks During Upper Amphibolite Facies Metamorphism,
Tobacco Root Mountains, Southwest Montana.

APPROVED BY THE MEMBERS OF THE THESIS COMMITTEE:

Michael L. Cummings, Chair

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Horace F. White

The purpose of this study is to characterize the
metasomatism that has taken place as a result of the
chemical incompatibility between mafic and metaultramafic
bulk compositions during high-grade regional metamorphism

in the Tobacco Root Mountains, southwest Montana. Metasomatism of these rocks took place by both diffusion- and infiltration-dominated processes. The result of these processes are characterized mineralogically and geochemically in the rocks.

On the basis of field mapping, the geology of the Branham Lakes cirque may be divided into five lithologic groups separated by structural boundaries or intrusive contacts: 1) an amphibolite unit, 2) an interlayered sequence of schist, gneiss, and amphibolite outcropping on the north wall of the cirque, 3) an interlayered sequence of gneiss and amphibolite in the southern part of the area, 4) a layered mafic intrusion, and 5) Late Cretaceous intrusions. The amphibolite unit is the focus of this study and is dominated by massive amphibolite. Metaultramafic bodies occur within the amphibolite, and metasomatic rocks have developed at the contacts between these bodies and surrounding amphibolite. Two types of contact relationships have been identified: 1) concordant contacts where the edge of a metaultramafic body is concordant to compositional layering in the enclosing amphibolite and 2) discordant contacts at the termini of a metaultramafic body where the contact is characterized by a shear trending at high angles to compositional layering in amphibolite. Lenses containing unique mineral assemblages represent dilatant zones in metasomatic rocks

at some discordant contacts.

The mineralogy of these rocks was determined by petrographic analysis of thin sections. Amphibolite displays a granoblastic texture and consists of the mineral assemblage hbl-pc-ap-qtz. Metaultramafic rocks contain the mineral assemblages opx-chrom, ol-chrom, or opx-ol-chrom. Opx and ol occur as large porphyroclasts and represent the oldest identifiable mineral assemblages in these rocks. Metasomatic rocks in amphibolite consist of the mineral assemblage hbl-ap, with an average modal abundance of 99% for hbl. Group I metasomatic rocks occur at concordant contacts between metaultramafic bodies and surrounding amphibolite, and are interpreted to have developed from diffusion-dominated processes. Group II metasomatic rocks occur at discordant contacts and are interpreted to have developed from the infiltration of metasomatizing fluids through a shear. Dilatent lenses in these shears contain the mineral assemblages hbl-gar, hbl-phl-gar, hbl-phl-hyp, and Mg-hbl-cumm. Group A metaultramafic rocks generally occur at concordant contacts with amphibolite and are generally the least altered, containing large porphyroclasts of opx or ol. Group B metaultramafic rocks occur in shears at discordant contacts and throughout the metaultramafic body and consist of highly fractured opx or ol porphyroclasts and have a high modal abundance of Mg-hbl (≈ 50 to 100%).

Mineral assemblages in all rock types are consistent with the conditions of high-grade metamorphism. Peak metamorphic conditions established elsewhere in the Tobacco Root Mountains are in the range 600-800° C and 4-6 kb pressure, indicative of the amphibolite facies of metamorphism.

Samples of each of these rock types were analyzed geochemically by INAA and XRF methods. The data indicates that metasomatic rocks have a composition that is intermediate between the compositions of amphibolite and metaultramafic rocks. This is readily observed in the average concentrations of MgO, CaO, and Cr. In amphibolite, MgO=9.22 wt%, CaO=12.32 wt%, and Cr=453 ppm; in Group I metasomatite, MgO=15.63 wt%, CaO=11.29 wt%, and Cr=787 ppm; and in Group A metaultramafic rocks, MgO=26.44 wt%, CaO=5.02 wt%, and Cr=2720ppm. These trends also occur in the concentrations of Na₂O, K₂O, Al₂O₃, Co, and REE. Lenses in metasomatic rocks at discordant contacts represent dilatent zones in which elements that were mobile in metasomatizing fluids precipitated out, forming unique mineral assemblages and chemical compositions. These lenses are highly concentrated in incompatible elements (eg. Ba, Cs), K₂O, Cr, and REE, and give an indication of which elements were mobile in the fluid phase of an infiltration-dominated system.

Each of these rocks were analyzed for element

mobility by NAAR and the isocon method of Grant (1986). The data from these methods indicate that, in general, 1) alkali metals tend to be mobile and move from mafic into ultramafic compositions, 2) CaO was relatively immobile, and MgO was mobile and moved into mafic from ultramafic compositions, 3) Al was mobile in the metasomatism of mafic rocks, but relatively immobile in ultramafic compositions, 4) REE and Hf were mobile and enriched in both compositions, 5) Th was mobile and depleted in both compositions, and 6) the incompatible elements Cs, Rb, and Ba were mobile and enriched in the fluid phase along shear zones.

METASOMATISM BETWEEN AMPHIBOLITE AND METAULTRAMAFIC ROCKS
DURING UPPER AMPHIBOLITE FACIES METAMORPHISM,
TOBACCO ROOT MOUNTAINS,
SOUTHWEST MONTANA

by
WILLIAM ROBERT McCULLOCH

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
GEOLOGY

Portland State University

1989

TO THE OFFICE OF GRADUATE STUDIES:

The members of the Committee approve the thesis of
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INTRODUCTION

Thompson (1959) defined metasomatism as "...any process involving a change in the bulk composition of the mineral assemblage." The driving mechanism of metasomatism is the chemical incompatibility between an assemblage and another medium with which it is in contact. Chemical components are lost or gained in response to chemical gradients across the contact between two incompatible bulk compositions. Examples where metasomatism has taken place include igneous intrusions where two contrasting bulk compositions are mechanically juxtaposed; metamorphism, where two rock types that are in chemical equilibrium under one set of conditions may react under another set of conditions; and hydrothermal alteration, where the fluid phase may be one of the incompatible bulk compositions. This study is concerned with metasomatism between mafic and ultramafic bulk compositions during high-grade regional metamorphism.

Korzhinskii (1970) distinguished two end-member types of metasomatism: diffusion and infiltration. Diffusion metasomatism involves components that are transported through stationary pore solutions and more rarely through a crystal lattice. It is typically of local extent,

rarely extending over a distance of several meters. In contrast, infiltration metasomatism may take place over many kilometers. During infiltration metasomatism, components are transported in a fluid moving through the rock. Although diffusion and infiltration are typically modeled by different thermodynamic schemes, they are rarely separable in natural systems.

Although diffusion and infiltration are often indistinguishable in natural systems, one may be the controlling process in a metasomatic system. That is, the change in bulk composition may be diffusion-controlled or infiltration-controlled. An example of a diffusion-controlled process is metamorphic differentiation (Fisher, 1973), in which components move through a stationary intergranular fluid in response to chemical potential gradients between incompatible minerals. Infiltration-dominated metasomatism may occur in vein systems during hydrothermal alteration.

Metasomatism during metamorphism has been studied experimentally by Vidale (1969) and in natural systems by Joesten (1974) for calc-silicate bulk compositions. Frantz and Mao (1976) and Brady (1977) modeled metasomatic reactions in ultramafic bulk compositions. Sanford (1982) studied metasomatic zoning in natural ultramafic bulk compositions developed under increasing metamorphic grades. These studies are typically concerned with

diffusion-controlled systems and the experimental and theoretical results match many natural systems quite well. The lack of infiltration-controlled studies most likely reflects a difficulty in constraining the pertinent variables in such systems.

Metasomatism between mafic and ultramafic rocks in the Branham lakes area of the Tobacco Root Mountains, southwest Montana (Figure 1), took place by diffusion and infiltration under conditions of high-grade regional metamorphism. The metasomatic system may be characterized mineralogically and geochemically so that element migration may be examined in both diffusion- and infiltration-dominated settings. This study will 1) examine the mineralogical and geochemical characteristics of the metasomatic system, 2) determine the mass redistribution in diffusion and infiltration dominated processes, and 3) present a model for the metasomatic processes between mafic and ultramafic rock types under these metamorphic conditions.

Figure 1. Location map of the study area in the Tobacco Root Mountains, southwest Montana. GR-Gravelley Range; HR-Highland Range; RR-Ruby Range; SMR-Southern Madison Range; NMR-Northern Madison Range; TRM-Tobacco Root Mountains (after Vitaliano and others, 1979).

GEOLOGIC SETTING

The Tobacco Root Mountains are in the northwestern part of the Archean Wyoming Province. They are among the northwesternmost outcrops of Archean basement exposed in the United States. Recently Mogk and Henry (1988) have interpreted the Archean basement of southwest Montana to have undergone a process of both tectonism and magmatic crustal evolution during the Archean. Deposition of coarse clastic and platform-type sediment in the northwestern Wyoming Province was followed by large-scale crustal shortening accompanied by isoclinal folding and nappe emplacement during granulite-facies metamorphism (ca. 2.70-2.75 b.y.a). This tectonic style is interpreted to be the result of continental collision against ancient sialic crust to the east. Montgomery (1988) described quartz monzonite stocks approximately 2.7 b.y. old in the Beartooth Mountains as having characteristics of syn- and post-collisional granite groups.

The Archean rocks of the Tobacco Root Mountains have been separated into the Cherry Creek group (Runner and Thomas, 1928), the Pony group (Tansley and others, 1933) and the Spuhler Peak formation (Gillmeister, 1972). However, Vitaliano and others (1979) argue that since

there is a lack of stratigraphic indicators for these group names and since stratigraphic determinations are very difficult, the use of the names "...should be held in abeyance." Such advice is followed in this study.

The age of amphibolite-grade metamorphism in the Tobacco Root Mountains was reported by Mueller and Cordua (1976) to be 2667 ± 66 m.y. for metamorphosed supracrustal rocks using the Rb/Sr dating method. A younger metamorphic event was reported by Giletti (1966) at approximately 1700 m.y. ago. The age of the Tobacco Root batholith was determined by K/Ar age dating to be between 77 and 72 m.y. by Vitaliano and others (1980).

Burger (1967) mapped the bedrock geology of the Sheridan District, which includes part of the study area (Figure 2). He identified an anthophyllite gneiss assemblage interlayered with an amphibolite-hornblende gneiss assemblage and a quartzite in the study area. These interlayered assemblages were interpreted to be separated from an intermediate gneiss assemblage by the Noble Fault. No fault plane or shear zone was recognized, but the fault is inferred by sharp contrasts between the anthophyllite gneiss assemblage and the intermediate gneiss. Hess (1967) also identified anthophyllite-bearing rocks on the west slope of Branham Peaks, and a green hornblende gneiss was identified in the area of Branham Lakes.

Figure 2. Location of the study area in the Branham Lakes cirque. The shaded area is the extent of the area mapped by Burger (1967) in the study area.

Gillmeister (1972) reported an unconformity between amphibolite of mafic composition and supracrustal rocks belonging to the Cherry Creek Group and Pony group in the central Tobacco Root Mountains. The amphibolite unit, termed the Spuhler Peak Formation, corresponds to the anthophyllite gneiss unit of Vitaliano and others (1979). The presence of an unconformity is based on 1) difference in rock type, 2) differences in structural trends, and 3) the lack of amphibolite dikes in the amphibolite unit that are present in the supracrustal rocks.

METHODS

Two summer field seasons in the area produced two maps; one at 10 cm = 1.266 km (Plate 1), the other at 1 cm = 12 m (Plate 2). The first map is a geologic map of the Branham Lakes cirque showing the distribution of major rock types and structures. The second map is a plane-table map of a portion of the area that shows the relationships of the metasomatic zones, shear zones, amphibolite and metaultramafic lenses.

Sampling in the area was for two purposes. The first purpose was to represent all the major rock types occurring in the Branham Lakes cirque. The second purpose was related to a study of metasomatism between the amphibolite unit and metaultramafic bodies. Sampling for this purpose was done with three goals in mind:

- 1) to determine the extent of chemical or metamorphic effects related to the emplacement of the Tobacco Root batholith;
- 2) to characterize each rock type mineralogically and chemically, and to identify major textural differences within each rock type;
- 3) to identify and describe the metasomatic processes that were taking place between the amphibolite unit

and ultramafic bodies chemically, mineralogically, and texturally.

Petrography was performed by the author on 43 thin sections representing the major rock types and textures of samples related to metasomatism, and some other rock types in the area. X-ray diffraction (XRD) was used as an aid in the identification of some minerals and was performed by the author at Portland State University.

Whole rock major element oxide concentrations for eleven samples and whole rock major element oxide and trace element concentrations for eight samples were determined by X-ray fluorescence (XRF) under the supervision of Dr. Peter Hooper at Washington State University. Trace element and rare earth element (REE) concentrations were determined for 67 samples by instrumental neutron activation analysis (INAA) by the author at Portland State University. Selected samples were irradiated for neutron activation autoradiography (NAAR) and analyzed by the method outlined in Beeson and Beeson (1980). Specific gravity was determined by use of a triple beam balance. An analysis of error for these methods is presented in the appendix.

ROCK UNITS

Upper and lower Branham Lakes are located in a glaciated terrain of high relief in the south-central part of the Tobacco Root Mountains (Figure 1). Five lithologic groups, separated by structural boundaries or intrusive contacts, occur within the Branham Lakes cirque. The rocks include 1) an amphibolite unit (Aa), 2) an interlayered sequence of schist, gneiss, and amphibolite cropping out on the north wall of the cirque (Ams), 3) an interlayered sequence of gneiss and amphibolite in the southern part of the cirque (Ams), 4) a layered mafic intrusion (Alm), and 5) Late Cretaceous intrusions (Ki). Plate 1 is a geologic map of the area showing the distribution of these lithologic groups. Within the amphibolite unit are metaultramafic bodies (Amu) containing orthopyroxene and olivine. Metasomatic rocks have developed along the contacts between these metaultramafic bodies and the enclosing amphibolite. The focus of this thesis is metasomatism. Therefore the amphibolite unit (Aa) and metaultramafic rocks contained therein will be described in greater detail than the other lithologic groups.

AMPHIBOLITE UNIT

Field Relations

The major rock type in the amphibolite unit is a massive to compositionally layered granoblastic amphibolite (Aa on Plates 1 and 2). Compositional layering is produced by the relative proportions of hornblende and plagioclase. Modal hornblende abundance is 10-40% in light-colored layers and 70-90% in dark-colored layers. Modal abundances for selected thin sections are presented in Table I. Garnet-bearing bands as thick as 8 meters occur rarely within the generally garnet-free amphibolite. These bands contain up to 35% garnet with 55% hornblende and 10% plagioclase.

Compositional layering displays a variety of structures. Boudinage structures occur in areas of intense folding resulting in boudins of light-colored amphibolite in a dark-colored amphibolite matrix. The axial planes of folds and the apparent long dimension of boudins are generally parallel to the overall orientation of compositional layering.

Equidimensional to elongate bodies of metaultramafic rock occur within amphibolite (Amu on Plates 1 and 2). The thickness of these bodies is generally 10 to 20 meters, but they are variable in length, ranging from 10 to a few hundred meters. Three types of metaultramafic

TABLE I
MODAL ABUNDANCES OF SELECTED THIN SECTIONS^{1,2}

AMPHIBOLITE											
<u>Sample No.</u>	<u>Hbl</u>	<u>Pc</u>	<u>Ap</u>	<u>Qtz</u>	<u>Gar</u>	<u>Tita</u>	<u>Clz</u>	<u>Op</u>	<u>Unk</u>	<u>Total Points</u>	
85-34	65.8	33.6	0.4	-	-	-	-	-	0.2	500	
85-35	69.6	24.2	0.4	1.0	0.2	1.3	0.4	2.9	-	1000	
85-92-1	65.8	31.4	0.4	2.4	-	t	-	-	-	500	
86-19	64.6	35.0	0.2	0.2	-	t	-	-	-	500	
METASOMATITE											
<u>Sample No.</u>	<u>Hbl</u>	<u>Pc</u>	<u>Ap</u>	<u>Qtz</u>	<u>Trem</u>						<u>Total Points</u>
85-31A	99.6	-	0.4	-	-						500
86-15	99.0	0.8	0.4	t	-						500
85-67	99.0	-	0.4	-	0.6						500
LENSES IN SHEAR ZONES											
<u>Sample No.</u>	<u>Hbl</u>	<u>Phl</u>	<u>Hyp</u>	<u>Ap</u>	<u>Sp</u>	<u>Cord</u>	<u>Gar</u>	<u>Pc</u>	<u>Opx</u>		
85-116B	48.8	20.6	10.6	t	18.4	t	-	-	-	500	
85-38	20.8	-	-	-	-	-	16.0	27.5	21.8		
85-29	-	-	-	-	-	-	-	-	-		
LENSES IN SHEAR ZONES (CONT.)											
<u>Sample No.</u>	<u>Bio</u>	<u>Mg-Hbl</u>	<u>Cumm</u>	<u>Mg-Chl</u>	<u>Op</u>	<u>Unk</u>					<u>Total Points</u>
85-116B	-	-	-	-	0.4	1.2					500
85-38	3.2	-	-	-	10.7	-					600
85-29	-	69.0	28.0	1.2	-	1.8					500

TABLE I
MODAL ABUNDANCES OF SELECTED THIN SECTIONS
(continued)

METAULTRAMAFIC ROCKS									
<u>Sample No.</u>	<u>Opx</u>	<u>Ol</u>	<u>Mg-Hbl</u>	<u>Trem</u>	<u>Tc</u>	<u>Mg-Chl</u>	<u>Op</u>	<u>Unk</u>	<u>Total Points</u>
85-87E	-	3.5	94.0	-	-	-	2.0	0.5	200
85-39	-	-	75.6	23.6	-	-	0.2	0.6	500
85-41	0.8	18.8	69.7	-	-	-	10.7	-	1000
85-113	66.0	0.6	27.2	-	-	-	5.8	0.4	500
86-74	-	-	-	-	74.0	16.8	9.2	-	250

1. All values are in modal percent.
2. Mineral abbreviations are listed in Table II.

TABLE II
MINERAL ABBREVIATIONS

ap	apatite
bio	biotite
chl	chlorite
chrom	chromite
clz	clinozoisite
cumm	cunningtonite
gar	garnet
hbl	hornblende
hyp	hypersthene
mt	magnetite
Mg-chl	Mg-chlorite
Mg-hbl	Mg-hornblende
musc	muscovite
ol	olivine
op	opaque
opx	orthopyroxene
pc	plagioclase
phl	phlogopite
sp	spinel
tc	talc
tita	titanite
trem	tremolite

rocks may be distinguished on the basis of the modal abundances of orthopyroxene and olivine. These types contain either 1) predominately orthopyroxene, 2) predominately olivine or 3) approximately equal proportions of olivine and orthopyroxene. Many of these bodies have been altered to some degree, resulting in a variety of mineral assemblages.

The contacts of these bodies with amphibolite are obscured by the occurrence of metasomatic rocks, but two types of contact relationships may be defined on the basis of the geometry of the metaultramafic bodies relative to amphibolite. These are 1) concordant contacts where the edge of a metaultramafic body is concordant to compositional layering in the enclosing amphibolite, and 2) discordant contacts at the termini of a metaultramafic body where the contact is characterized by a shear trending at high angles to compositional layering in amphibolite.

On the basis of field, petrographic, and geochemical data, the following relationships have been developed for the contacts between amphibolite and metaultramafic bodies:

1) At concordant contacts in which there is no evidence of cross-cutting relationships of metasomatic rocks and amphibolite, nearly monomineralic granoblastic coarse-grained hornblende metasomatite (Group I

metasomatites) forms sharp contacts with a metaultramafic body, but is gradational into amphibolite. The metasomatic rocks contain over 95% modal hornblende. Grains average 2 cm long. The rocks are monomineralic adjacent to the contact with the metaultramafic body but the modal abundance of plagioclase increases relative to hornblende toward the amphibolite. The grain size of hornblende decreases toward the amphibolite.

Metaultramafic rocks adjacent to concordant contacts are commonly less sheared than at other contacts and contain either large porphyroblasts of orthopyroxene up to 15 cm long or porphyroblasts of olivine and orthopyroxene averaging 5 cm in diameter. Shear zones in metaultramafic rocks contain green Mg-hornblende averaging 2 cm long.

2) At some concordant contacts apophyses of monomineralic hornblende metasomatite, projecting off the main concordant metasomatite band, cross-cut amphibolite (Figure 3). The metasomatic bands form sharp contacts with the amphibolite and metaultramafic body. The apophyses of metasomatic rocks are generally less than a meter in length and form sharp contacts with the amphibolite. These apophyses appear to be local shears cutting amphibolite.

Metaultramafic rocks adjacent to this type of contact are commonly highly sheared, and in places contain areas of monomineralic rock consisting of Mg-hornblende.

Figure 3. Schematic sketch of an apophysis of metasomatic rock cutting amphibolite off the main metasomatic band. Scale is approximate only.

Olivine and/or orthopyroxene porphyroblasts are highly fractured in these rocks.

3) At discordant contacts defined by shears terminating metaultramafic bodies and extending into and cross-cutting amphibolite, hornblende metasomatite is commonly coarser grained than in the concordant contacts. Hornblende averages 2 to 5 cm long in these settings and may attain lengths up to 15 cm. Subidioblastic garnet, up to 6 cm in diameter, occurs locally in these rocks. The contact between the metasomatite and amphibolite is sharp. The contact between metasomatite and metaultramafic rocks is characterized by shearing of the metaultramafic rocks. Shear zones in metaultramafic rocks contain Mg-hornblende.

Lenses containing rocks with unique mineral assemblages occur within metasomatite in these settings. Three types of lenses occur: 1) garnet-hornblende lenses, 2) phlogopite-hornblende±garnet±hypersthene lenses, and 3) Mg-hornblende-cummingtonite lenses. Garnet-hornblende lenses are granoblastic and contain hornblende interstitial to garnet. The garnet averages 1 mm in diameter. The lenses (Figure 4) are commonly less than 20 cm in diameter, although larger lenses do occur. The contact between these lenses and the surrounding metasomatite is gradational, with the modal abundance of garnet decreasing relative to hornblende toward the metasomatite.

Figure 4. Photograph of a garnet-rich lens within metasomatite. The metasomatite occurs in a shear zone cutting amphibolite.

Lenses containing phlogopite-hornblende assemblages average about a meter in length. They are granoblastic and commonly contain phlogopite as the most abundant mineral, with variable modal abundances of hornblende and locally orthopyroxene or garnet. The contact between these lenses and the surrounding metasomatite is sharp.

Mg-hornblende-cummingtonite lenses are angular (Figure 5) and average a meter in diameter. Phlogopite occurs locally. Mg-hornblende and cummingtonite are prismatic and aligned, imparting a strong lineation to these lenses. The trend of the lineation is discordant between adjacent lenses and to the trend of the metasomatic band in which it occurs. Locally the lineation is folded into sharp chevron-like folds. Contact with the surrounding metasomatite is gradational; cummingtonite decreases in modal abundance relative to Mg-hornblende, which darkens in color and increases in grain size toward the edge of the lens.

A second group of shear zones occur within the amphibolite and metasomatic rocks and commonly display a strong tectonite fabric (Figure 6). Plate 2 is a geologic map illustrating the relationship of these shear zones to other rock types.

These shear zones contain porphyroblasts of sillimanite in a matrix of quartz, feldspar, garnet, and biotite. Shear zones range from a few meters to tens of

Figure 5. Photograph of a Mg-hornblende-cummingtonite lens within metasomatite. The metasomatite occurs in a shear zone cutting amphibolite.

Figure 6. Photograph of the tectonite fabric in shear zones.

meters in width and have been traced for distances of a few meters to over a hundred meters. The trends of shear zones range from generally parallel to the local trend of compositional layering in the enclosing amphibolite to strongly cross-cutting. The former groups are more common. Compositional layering in amphibolite adjacent to shear zones is commonly deformed. Asymmetric folds are common in these areas and the axial planes of the folds are subparallel to the orientation of the shear zones. Clasts of amphibolite occur within shear zones.

Compositional layering within amphibolite clasts is commonly folded and discordant to banding in the shear zone, which bows around the boudins. Bodies of exotic rock types occur within some larger shear zones. A metaultramafic body of the type that occurs elsewhere in the amphibolite occurs in one shear zone, which also contains bodies of banded iron formation and quartzite.

Hornblende- and/or biotite-bearing quartz-feldspar pegmatite dikes (P_{Ep}) cross-cut rock types in the amphibolite unit. They are generally less than a meter wide and traceable for up to half a kilometer in places. The pegmatite dikes are commonly straight, but are deformed where they cross shear zones. Hornblende and biotite grains as large as 50 cm have been observed in the pegmatite, but more typically average 5 cm in length.

The entire amphibolite unit, which includes

amphibolite, metaultramafic bodies, metasomatite, and shear zones, is cross-cut by small quartz-feldspar veins, rarely over 5 mm in width, that in places make up as much as 10% of the rock volume, but are lacking elsewhere. These veins are most common in amphibolite and rare in metaultramafic bodies. Some of the veins contain pyrite. Although the trace of these veins are generally straight, they often converge and cross-cut one another.

Petrography

Amphibolite (Figure 7) consists of hornblende, plagioclase, quartz, and apatite; garnet and titanite occur locally. Assemblages are listed in Table III, modal analyses in Table I. Hornblende, plagioclase, and quartz average 2 mm in diameter and define a granoblastic texture. Hornblende, plagioclase and quartz are xenoblastic and generally display mutually smooth to finely seriate grain boundaries. Each of these minerals also occurs as inclusions less than 0.5 mm in diameter within each other. Apatite occurs as inclusions averaging 0.1 mm in diameter within hornblende, plagioclase, and quartz and at grain boundaries between these minerals.

The optical properties of hornblende and plagioclase are listed in Table IV. Plagioclase composition is difficult to determine since twinning is not well developed. Patchy zoning is common. Optical analysis of 50 plagioclase grains for refractive index by the Becke

Figure 7. Photomicrograph of amphibolite under plane-polarized light. This sample contains equigranular hornblende (hbl) and plagioclase (pc). Field of view is approximately 2 cm across.

TABLE III
MINERAL ASSEMBLAGES¹

AMPHIBOLITE

hbl-pc-ap-qtz

hbl-pc-ap-qtz $\pm$ gar $\pm$ tita $\pm$ op

METASOMATITE (Group I)

hbl-ap

hbl-ap-pc

hbl-ap-gar

SHEARS CUTTING AMPHIBOLITE (Group II)

hbl-ap

hbl-ap $\pm$ trem

hbl-ap-rutile(?) $\pm$ qtz

LENSES IN SHEARS CUTTING AMPHIBOLITE

hbl-gar

hbl-phl-gar $\pm$ ap $\pm$ op

hbl-phl-hyp-op $\pm$ ap

Mg-hbl-cumm $\pm$ phl

METAUltrAMAFIC

opx-chrom

ol-chrom

ol-opx-chrom

METASOMATIC ASSEMBLAGES IN METAUltrAMAFIC

Mg-hbl-cumm

SHEARS CUTTING ULTRAMAFIC

Mg-hbl

Mg-hbl-trem-op

1. Mineral abbreviations are listed in Table II.

TABLE IV
OPTICAL PROPERTIES OF SELECTED MINERALS

<u>Mineral</u>	<u>optic sign</u>	<u>2V angle</u>	<u>pleochroism</u>	<u>maximum extinction angle</u>
AMPHIBOLITE				
hornblende	-	75-80	X=light green Y=olive green Z=brownish green	17
plagioclase	-	80-110	colorless	
METASOMATITE				
hornblende	-	80	X=pale green Y=olive green Z=dark green	17
LENSES WITHIN SHEARS				
a. hornblende-phlogopite lenses				
hornblende	-	85	X=colorless Y=olive green Z=blue green	17
phlogopite	-	5	X=colorless Y=light green Z=olive green	

TABLE IV
OPTICAL PROPERTIES OF SELECTED MINERALS
(continued)

hypersthene	-	60-70	X=pink Y=colorless Z=pale green	parallel
b. garnet-hornblende lenses				
hornblende	-	85-90	X=greenish yellow Y=yellowish green Z=light blue-green	17
c. Mg-hornblende-cummingtonite lenses				
Mg-hornblende	-	90	X=pale green Y=light green Z=green	15
cummingtonite	-	90	colorless	18
METAULTRAMAFIC				
bronzite	-	85-90	X=light pink Y=colorless Z=colorless	parallel
olivine	-	90	colorless	
Mg-hornblende	-	90	X=colorless to pale green Y=colorless to pale green Z=pale green	15

line method in oils indicates a range in anorthite content of An45 to An100. This range is supported by 2Vz angles in plagioclase ranging between 80° and 110° , indicating anorthite contents in the range An45 to An85. Plagioclase grains with 2Vz angles greater than 90° are more common than those with 2Vz angles less than 90° .

Titanite occurs in one sample in relatively high modal abundance (1.3%) and in trace amounts in other samples (Table I). It occurs as inclusions in plagioclase, hornblende, and quartz. Grains average 0.2 mm long and display xenoblastic to idioblastic forms. Garnet occurs locally in amphibolite as an inclusion within plagioclase. Grains average 0.5 mm diameter.

Metaultramafic assemblages consist of bronzite-chromite, bronzite-olivine-chromite, or olivine-chromite. Due to metasomatic alteration of these rocks, it is difficult to determine the pre-alteration modal abundances of bronzite and olivine. Additionally, the large size of bronzite and olivine porphyroclasts tend to bias any modal analysis of a part of the rock the size of a thin section. Modal analyses of selected thin sections are shown in Table I.

Bronzite-chromite assemblages contain large porphyroclasts of bronzite (En85-87) up to 15 cm in length. Porphyroclasts are xenoblastic to subidioblastic and equant to prismatic. Opaques are rare as inclusions

within bronzite. Olivine-bronzite-chromite and olivine-chromite assemblages contain porphyroblasts of bronzite and olivine averaging 8 mm in diameter. Grain size is fairly consistent in these rocks. The porphyroblasts are xenoblastic and equant. Grain boundaries between olivine and bronzite are sharp and regular. Porphyroblasts in all three assemblages are commonly highly fractured; olivine more so than bronzite. Opaque minerals occur within fractures in olivine, but rarely occur in fractures or as inclusions in bronzite.

Cleavage traces in bronzite are not well developed, masking the parallel extinction and making optical determination difficult. The optical properties of bronzite and olivine are listed in Table IV. XRD of bronzite produces a diffractogram indicative of orthopyroxene (Figure 8). The $2V_z$ angle indicates an enstatite content of En85-87. The $2V_z$ angle of olivine indicates a forsterite content of Fo85.

Metasomatic replacement of amphibolite resulted in essentially monomineralic assemblages containing over 95% modal hornblende. Assemblages are listed in Table III, and modal analyses of selected thin sections in Table I. Hornblende averages 2-5 mm in length, but may be as large as 15 cm long. It is prismatic to equant, defining a granoblastic texture (Figure 9). The optical properties of hornblende in metasomatite are listed in Table IV.

Figure 8. Portion of a diffractogram of orthopyroxene. The major peaks used to identify the mineral are shown.

Figure 9. Photomicrograph of hornblende metasomatite under plane-polarized light. This sample shows the high modal abundance of hornblende. Field of view is approximately 2 cm across.

Inclusions of apatite and, less commonly, quartz occur within hornblende and along grain boundaries of hornblende and are less than 0.1 mm in diameter. Sparse plagioclase occurs in places along grain boundaries of hornblende, commonly at triple junctions. An unidentified mineral resembling rutile in optical properties occurs locally as subidioblastic grains averaging 0.5 mm long. This mineral was not identified as rutile because its reflected light properties are not indicative of rutile. Idioblastic porphyroblasts of garnet occur locally in metasomatite and are up to 6 cm in diameter. Rare sulfide minerals occur within hornblende. Where metasomatite is gradational into amphibolite, a transitional rock type occurs that has a similar mineralogy and texture as amphibolite except the modal proportion of hornblende to plagioclase is greater toward the metasomatite. Grain size of hornblende also increases toward the metasomatite. The gradational boundary in which these rocks occur is commonly less than 10 cm wide.

Lenses with unique mineral assemblages occur within the metasomatite. The assemblages are listed in Table III. Photomicrographs of samples from some of these lenses are shown in Figure 10. The modal abundance of each mineral is variable from lens to lens, however the lenses are commonly rich in either phlogopite or garnet. Table I includes modal analyses of selected samples.

Figure 10a. Photomicrograph of a hornblende-phlogopite lens under plane-polarized light showing subidioblastic hornblende (hbl) and phlogopite (phl). Field of view is approximately 2 cm across.

Figure 10b. Photomicrograph of a hornblende-phlogopite lens under plane-polarized light showing a hypersthene porphyroblast (hyp) embayed by hornblende (hbl) and phlogopite (phl). Field of view is approximately 4 mm across.

Figure 10c. Photomicrographs of garnet-rich lenses. The top photomicrograph shows garnet (gar) and hornblende (hbl) under plane-polarized light. Field of view is approximately 2 cm across.

Bottom photomicrograph shows symplectite rims (s) around garnet (gar) under crossed polars. Field of view is approximately 4 mm across.

Hornblende and phlogopite are subidioblastic to idioblastic (Figure 10a). Where these minerals occur together, they have mutually smooth grain boundaries. Phlogopite ranges in size from 0.2 to 3 mm long and hornblende 0.2 to 4 mm long. In places, phlogopite defines a poorly developed schistosity. The optical properties of hornblende and phlogopite in these lenses are listed in Table IV.

In some hornblende-phlogopite lenses, hypersthene occurs in two textural settings: 1) as xenoblastic porphyroblasts up to 1 cm in diameter, and 2) as small clusters of grains less than 0.1 mm in diameter associated with apatite along grain boundaries of hornblende and phlogopite. Hornblende and phlogopite embay hypersthene porphyroblasts (Figure 10b). Hypersthene is identified on the basis of extinction angle, $2V_z$ angle, and pleochroism (Table IV). Green spinel is common in some samples as clusters of grains along grain boundaries of hornblende, phlogopite, and hypersthene, and as inclusions in these minerals. The grain size of spinel is generally less than 0.2 mm in diameter. Apatite, hornblende, and phlogopite also occur as small inclusions in spinel-bearing clusters.

Garnet is commonly highly fractured and ranges from 1 to 8 mm in diameter (Figure 10c). These grains are equant and subidioblastic. In garnet-rich lenses, the garnet and interstitial hornblende defines a granoblastic texture.

Large grains of a sulfide mineral defining a rectangular form occur locally in phlogopite-rich rocks. Where they occur, adjacent phlogopite is brownish in color, grading into the common green color away from the sulfide.

Mg-hornblende-cummingtonite lenses in metasomatite contain the assemblage Mg-hornblende-cummingtonite $\pm$ biotite. Mg-hornblende and cummingtonite are commonly prismatic and less commonly equant. Prismatic grains define a lineation in the rock. Mg-hornblende is greater in modal abundance than cummingtonite (Table I) and biotite was observed in approximately equal modal abundance as cummingtonite in a few samples. The optical properties of Mg-hornblende and cummingtonite are listed in Table IV.

Metasomatic replacement of amphibolite occurred at the contact between amphibolite and metaultramafic bodies and in shears extending into amphibolite. Assemblages that occur within shears and at discordant contacts characterized by shears are identical to those described above. Assemblages occurring at concordant contacts are similar, but do not contain the lenses of unique mineral assemblages that are in rocks at discordant contacts.

Metasomatic assemblages within metaultramafic bodies include Mg-hornblende $\pm$ opaques and Mg-hornblende-tremolite $\pm$ opaques. Opaques are commonly more abundant as inclusions

in tremolite than in Mg-hornblende. These assemblages occur in variable modal proportions between samples. Modal analyses of selected thin sections are listed in Table I. Photomicrographs of metasomatic assemblages in metaultramafic rocks are shown in Figure 11. The major difference between these samples is the variable modal abundance of bronzite and olivine relative to Mg-hornblende.

Optically it is difficult to distinguish between Mg-hornblende and actinolite in these samples, possibly due to a solid solution between the two compositions at high temperatures and pressures (Robinson and others, 1982). Because of this difficulty, this mineral will be referred to as Mg-hornblende if it has the following optical properties: a pleochroic scheme of X= colorless to pale green, Y= colorless to pale green, Z= pale green, and a 2V angle of 90° , indicating a hornblende with high Mg/Fe ratios (Philips and Griffen, 1981).

Mg-hornblende is xenoblastic to subidioblastic and equant to prismatic. It commonly defines a granoblastic texture. However, alignment of prismatic grains occurs in some samples producing a weak lineation in the rock. Tremolite is fibrous and commonly forms lenses or pockets surrounded by Mg-hornblende. Tremolite is colorless in plane polarized light, and its fibrous form makes optical determination difficult. Mg-hornblende embays and occurs

Figure 11a. Photomicrograph of Mg-hornblende (Mg-hbl) occurring in shears cutting orthopyroxene porphyroclasts (opx) under plane-polarized light. Field of view is approximately 2 cm across.

Figure 11b. Photomicrograph of Mg-hornblende (Mg-hbl) occurring in shears cutting metaultramafic rocks containing fractured olivine porphyroclasts (ol) under plane-polarized light. Field of view is approximately 2 cm across.

Figure 11c. Photomicrograph of a Mg-hornblende (Mg-hbl)-tremolite (trem) metasomatic rock occurring in shears cutting metaultramafic rocks under plane-polarized light. Field of view is approximately 2 cm across.

in fractures within bronzite and olivine porphyroblasts. Mg-hornblende and cummingtonite also occur as aligned inclusions in bronzite. In some bronzite porphyroblasts, these inclusions are highly abundant, but may be absent in other porphyroblasts.

A set of reaction assemblages occur locally within amphibolite, metasomatite, lenses in metasomatite, and metaultramafic rocks. These assemblages are listed in Table V. The assemblage plagioclase-amphibole rims garnet in amphibolite. Plagioclase occurs as a fine-grained equigranular mosaic around garnet and fine-grained prismatic amphibole occurs within the plagioclase mosaic. Titanite in amphibolite is commonly rimmed by an opaque.

Garnet porphyroblasts in metasomatite are generally fractured. The fine-grained assemblage green chlorite-amphibole occurs within these fractures. This assemblage also rims garnet, separating the surrounding hornblende from the garnet. The unidentified mineral resembling rutile in metasomatite is rimmed by an opaque, and in some grains the mineral is entirely replaced by the opaque.

In garnet-rich lenses, the garnet is surrounded by a fine-grained symplectite rim of plagioclase and orthopyroxene (Figure 10c). At the outer boundary of the symplectite rim, an oxide occurs with granoblastic plagioclase and orthopyroxene. The oxide occurs between symplectite rims of adjacent garnet grains and between the

TABLE V
LOCAL REACTION ASSEMBLAGES¹

AMPHIBOLITE

clz-op; replacing hbl
chl; replacing hornblende
amphibole-pc; rimming gar
op; rimming tita

METAULTRAMAFIC

Mg-chl-opx-sp; occurs as patches

METASOMATITE

chl-amphibole-op; rimming gar
op; rimming rutile(?)

SHEARS CUTTING AMPHIBOLITE

pc-opx-mt±bio; symplectite rim around
gar in garnet-rich lenses
pc-opx-sp±phl; symplectite rim around
gar in hbl-phl lenses
bio-opx-pc-musc-op; pseudomorph of hornblende

1. Mineral abbreviations are listed in Table II.

symplectite rim of a garnet grain and hornblende. Biotite occurs throughout the lens and is associated with garnet, symplectite rims, and also occurs as a replacement of hornblende along grain boundaries and cleavage planes.

In phlogopite-rich lenses, garnet is rimmed by a symplectite of plagioclase and orthopyroxene. Fine-grained green spinel and phlogopite occur between adjacent symplectite rims. In places within these lenses, idioblastic hornblende is pseudomorphed by the fine-grained assemblage biotite-orthopyroxene-plagioclase(?)-muscovite-opaque. In the center of some pseudomorphs the hornblende is still present. Locally cordierite(?) partially rims spinel in these lenses.

The assemblage Mg-chlorite-orthopyroxene-spinel $\pm$ tremolite occurs locally in metaultramafic bodies. Tremolite occurs in rocks containing bronzite porphyroblasts, and is absent from those containing olivine. The assemblage occurs interstitial to Mg-hornblende, which is rimmed by the orthopyroxene, separating Mg-hornblende from Mg-chlorite. Mg-chlorite is fine-grained, fibrous to platy, and has a 2Vz of less than 10°. It is colorless in plane polarized light. Fine-grained orthopyroxene and green spinel occur with chlorite and are commonly less than 0.1 mm in diameter. Orthopyroxene displays a colorless to light-pink pleochroism and a 2V angle of 90°.

A variety of other replacement assemblages occur locally in metaultramafic bodies, and to describe all of them is beyond the scope of this project; however, a few are worth noting. In some samples serpentine occurs as a replacement of olivine. In places, biotite occurs with Mg-chlorite. In these samples, Mg-chlorite ranges in grain size up to 10 cm in diameter. In one sample orthopyroxene porphyroblasts are entirely pseudomorphed by talc. Subidioblastic grains of Mg-chlorite up to 0.5 mm long occur interstitially to the talc pseudomorphs. A modal analysis of this sample is shown in Table I.

INTERLAYERED SEQUENCE, NORTH WALL OF CIRQUE

The lithologies exposed on the southern flank of Branham Peaks and Mount Bradley include metaquartzite, biotite and muscovite schist, and amphibolite. Sulfide-rich and anthophyllite-bearing rocks occur locally. The contacts between lithologies are sharp and in many cases are healed fault surfaces that parallel compositionally defined contacts and that locally climb upward across lithologic units. The base of this sequence overlies the amphibolite unit. The contacts are marked, at least locally, by a metaquartzite juxtaposed against amphibolite. Large drag folds occur above this main fault (Figure 12). The sequence of lithologies appears to be juxtaposed within an imbricate fault system. This

Figure 12. Photograph of the west flank of Branham Peaks. The dashed lines represent the approximate locations of faults. An interlayered sequence of schist, amphibolite, and quartzite (Ams) overlie the faults. The amphibolite unit (Aa) occurs below the faults.

complicated fault system interleaves amphibolite, metaquartzite, and mica schists.

INTERLAYERED SEQUENCE, SOUTHERN PART OF AREA

The lithologies exposed on either side of the north fork of Mill Creek include quartzofeldspathic gneiss, amphibolite, garnet gneiss, and meta-iron formation. These lithologies occur as layers that range in thickness from 5 cm to greater than 100 meters. Contacts between layers are sharp. The contact of this sequence against the amphibolite unit is marked by a large shear zone that is greater than 100 meters wide (Plate 1). The orientation of compositional layering in the amphibolite unit adjacent to the shear zone is parallel to subparallel to the orientation of the shear zone. The orientation of layering and of lithologic units in interlayered rocks adjacent to the shear zone are discordant to the orientation of the zone. Boudins of rocks from the interlayered sequence and amphibolite occur within the shear zone.

Figure 13 contains pi plots of trends of compositional layering in the amphibolite unit and compositional layers in the interlayered sequences. The amphibolite unit and the interlayered sequence on the north wall of the cirque display similar plots. The interlayered sequence in the southern part of the area

Figure 13. Pi plots on a stereonet of the poles to the orientation of compositional layering in the amphibolite (plot A), the interlayered sequence on the flank of Branham Peaks (plot B), and the interlayered sequence in the southern part of the area (plot C).

displays a plot that is different from those produced by the amphibolite unit and northern interlayered rocks

LAYERED MAFIC INTRUSION

A layered mafic intrusion crops out in the northeastern part of the area on Mount Bradley and Lady of the Lakes Peak and in the northwestern part of the area on the southwest flank of Branham Peaks (Plate 1). The intrusion consists of layered clinopyroxenite, websterite, gabbro, and anorthositic gabbro. Primary igneous textures are well preserved (Figure 14). In some samples, particularly the gabbroic samples, clinopyroxene is partially replaced to pseudomorphed by hornblende. The base of the intrusion is exposed on the flank of Mount Bradley where a shear zone within the amphibolite unit is truncated against the ultramafic base of the intrusion. The main exposed body of the intrusion is in contact with the northern interlayered sequence on Mount Bradley and the southern interlayered sequence on Lady of the Lakes Peak. On Mount Bradley the roof of the intrusion is metaquartzite (Figure 15).

The intrusion has been dissected by faults. Tectonically displaced blocks of the intrusion occur north of the main body and are bounded by interlayered rocks.

A small gabbroic block tentatively correlated to the intrusion occurs on the southwest flank of Branham Peaks

Figure 14. Photograph of relic cyclic layering in a gabbroic layer in the layered mafic intrusion.

Figure 15. Photograph showing the contact (dashed line) of the layered mafic intrusion (Alm) with overlying quartzite (Ams).

(Plate 1) and is bounded by the amphibolite unit. It is in contact with a metaultramafic body which in hand samples appears to be recrystallized at the contact with the gabbro. Along the margin of the gabbro adjacent to the metaultramafic body, the gabbro is finer grained and contains a higher modal abundance of hornblende than the interior of the block.

LATE CRETACEOUS INTRUSIONS

Late Cretaceous intrusions (Ki) cross-cut all other lithologic groups in the area. Intrusions include dikes, small stocks and the southern exposure of the Tobacco Root batholith. The batholith consists of coarse-grained phyrlic biotite quartz monzonite with phenocrysts of potassium feldspar up to 5 cm in length. Stocks, ranging in size from 10 meters to greater than 500 meters in diameter, generally consist of fine- to medium-grained phyrlic hornblende monzonite with phenocrysts of hornblende up to 1 cm in length. Locally intrusive breccia has developed along the margin of some stocks (Figure 16). Clasts in the breccia include all rock types occurring in the area. Dikes are commonly very fine grained phyrlic monzonite with phenocrysts of hornblende. They are variable in length and width and generally pinch out on the ends.

Other stocks (K(?)i) containing a higher modal

Figure 16. Photograph of intrusive breccia in a felsic stock. All local rock types are represented as clasts in these breccias.

abundance of hornblende crop out in the southern portion of the area (Plate 1). These stocks contain altered glomerocrysts of hornblende up to 1 cm in diameter. Skarn occurs locally and consists of bands containing epidote+ grossular, epidote, and diopside. Areas of mafic rock types containing 40% biotite, 50% hornblende, and 10% feldspar occur locally within these stocks.

A serpentinite body of questionable age occurs in the southern portion of the area within quartzofeldspathic gneiss. It is 13 meters thick and contains a relic but distinctly magmatic texture. Serpentine has entirely replaced primary olivine (Figure 17).

Figure 17. Photomicrograph of relic dunite textures in serpentinite under plane-polarized light. The magnetite (opaque) defines the relic grain boundaries between primary olivine grains, which have been replaced by serpentine. Field of view is approximately 2 cm across.

GEOCHEMISTRY

The locations of all samples subjected to geochemical analysis are shown in Plate 3. The amphibolite unit, which includes amphibolite, metaultramafic bodies within amphibolite, and metasomatic rocks developed between amphibolite and metaultramafic bodies, was analyzed in greater detail than other rock units and will be emphasized in this section.

AMPHIBOLITE UNIT

The amphibolite, metasomatites, and metaultramafic rocks are readily distinguished from each other on the basis of major element oxides and trace element concentrations. Geochemical data from each rock type are presented in Tables VI-XV. These distinctions are also evident in the CIPW norms (Tables VI-X). When compositions are plotted on an ACF diagram, each rock type defines a distinct compositional field (Figure 18). The metasomatite field lies between those of the metaultramafic and amphibolite rocks. These rocks are further distinguishable on the basis of major element oxide and trace element ratios. Table XVI contains ratios of CaO/MgO , $\text{MgO}/(\text{MgO}+\text{FeO})$, La/Sm , and Fe/Sc .

TABLE VI
MAJOR ELEMENT CONCENTRATIONS AND
CIPW NORMS FOR AMPHIBOLITE

	<u>85-34</u>	<u>85-35</u>	<u>86-23</u>	<u>86-33</u>	<u>86-19</u>
SiO ₂	48.47	50.16	48.65	47.96	51.36
Al ₂ O ₃	16.41	13.78	15.90	14.21	15.20
TiO ₂	0.49	1.84	0.43	0.47	0.40
FeO	9.68	13.82	9.29	12.78	8.57
MnO	0.26	0.26	0.27	0.24	0.30
CaO	12.44	10.56	13.50	13.67	11.41
MgO	9.77	6.56	10.18	9.34	10.26
K ₂ O	0.22	0.43	0.17	0.10	0.38
Na ₂ O	2.18	2.39	1.43	1.14	1.98
q	-	5.67	-	1.86	1.82
or	1.30	2.52	1.00	0.59	2.25
al	18.45	20.22	12.10	9.65	16.75
an	34.34	25.60	36.47	33.36	31.47
di	17.82	15.73	20.44	21.64	16.93
hed	3.47	4.76	3.74	5.90	2.89
en	8.31	9.05	15.16	13.23	17.71
fer	1.86	3.14	3.18	4.14	3.47
fo	5.44	-	0.51	-	-
fa	1.34	-	0.12	-	-
mt	6.54	9.34	6.28	8.63	5.79
il	0.93	3.49	0.82	0.89	0.76
ap	0.21	0.45	0.02	0.01	0.05

TABLE VII
MAJOR ELEMENT CONCENTRATIONS AND
CIPW NORMS FOR GROUP I
METASOMATITE

	<u>85-31A</u>	<u>86-15</u>	<u>86-16</u>
SiO ₂	47.26	50.41	48.11
Al ₂ O ₃	13.32	9.42	10.73
TiO ₂	0.39	0.37	0.47
FeO	11.99	9.75	10.60
MnO	0.26	0.34	0.35
CaO	11.42	11.07	11.39
MgO	13.01	17.04	16.84
K ₂ O	0.27	0.27	0.32
Na ₂ O	2.02	1.11	1.03
P ₂ O ₅	0.063	-	-
q	-	-	-
or	1.60	1.60	1.89
al	17.09	9.39	8.72
an	26.48	19.92	23.71
di	19.92	24.66	22.95
hed	3.74	2.96	2.95
en	6.03	27.05	18.21
fer	1.30	3.72	2.69
fo	12.01	2.78	9.18
fa	2.85	0.42	1.49
mt	8.11	6.58	7.16
il	0.74	0.70	0.89
ap	0.14	-	-

TABLE VIII
MAJOR ELEMENT CONCENTRATIONS AND
CIPW NORMS FOR GROUP II
METASOMATITE

	<u>85-67</u>
SiO ₂	51.27
Al ₂ O ₃	8.93
TiO ₂	0.42
FeO	1.86
MnO	0.24
CaO	10.37
MgO	14.97
K ₂ O	0.16
Na ₂ O	1.63
P ₂ O ₅	0.135
q	1.25
or	0.95
al	13.79
an	16.58
di	23.25
hed	3.70
en	26.51
fer	4.84
fo	-
fa	-
mt	8.02
il	0.80
ap	0.31

TABLE IX
MAJOR ELEMENT CONCENTRATIONS AND
CIPW NORMS FOR GROUP A
METAULTRAMAFIC ROCKS

	<u>85-32A</u>	<u>85-32D</u>	<u>85-113</u>	<u>85-111</u>	<u>85-112</u>
SiO ₂	52.05	55.54	51.69	48.59	45.78
Al ₂ O ₃	6.85	3.56	5.09	4.68	5.67
TiO ₂	0.30	0.19	0.28	0.31	0.30
FeO	13.37	13.15	11.07	7.83	10.76
MnO	0.28	0.28	0.28	0.29	0.37
CaO	4.31	2.59	4.82	9.26	4.16
MgO	22.09	24.21	25.57	28.20	32.15
K ₂ O	0.03	0.01	0.02	0.04	-
Na ₂ O	0.66	0.44	0.63	0.29	0.24
P ₂ O ₅	0.044	0.026	0.544	0.363	0.006
q	3.58	8.79	0.01	-	-
or	0.18	0.06	0.12	0.24	-
al	5.58	3.72	5.33	2.45	2.03
an	15.64	7.71	11.00	11.35	14.39
di	3.84	3.49	6.77	23.87	4.54
hed	0.49	0.41	0.62	1.39	0.33
en	53.25	58.69	60.56	29.63	33.60
fer	7.73	7.82	6.32	1.98	3.77
fo	-	-	-	20.71	31.10
fa	-	-	-	1.52	2.82
mt	9.03	8.89	7.48	5.29	7.26
il	0.57	0.36	0.53	0.59	0.57
ap	0.09	0.07	1.28	0.86	0.01

TABLE X
MAJOR ELEMENT CONCENTRATIONS AND
CIPW NORMS FOR GROUP B
METAULTRAMAFIC ROCKS

	<u>85-78</u>	<u>85-82</u>	<u>85-85</u>	<u>86-10</u>
SiO ₂	50.97	49.01	49.42	46.73
Al ₂ O ₃	5.87	4.76	4.91	7.12
TiO ₂	0.32	0.25	0.26	0.36
FeO	11.70	12.03	12.21	13.27
MnO	0.27	0.27	0.29	0.47
CaO	6.99	5.59	4.78	6.54
MgO	22.94	27.23	27.44	24.39
K ₂ O	0.03	0.05	0.03	0.32
Na ₂ O	0.86	0.73	0.64	0.40
P ₂ O ₅	0.042	0.064	0.024	0.033
q	-	-	-	-
or	0.18	0.30	0.18	1.89
al	7.28	6.18	5.42	3.38
an	12.07	9.56	10.44	16.69
di	15.92	12.80	9.46	10.97
hed	1.69	1.19	0.89	1.29
en	45.00	39.34	45.32	32.99
fer	5.47	4.20	4.89	4.45
fo	3.34	15.81	13.07	15.90
fa	0.45	1.86	1.56	2.36
mt	7.90	8.13	8.25	8.96
il	0.61	0.47	0.49	0.68
ap	0.09	0.14	0.05	0.08

TABLE XI
MAJOR AND TRACE ELEMENT CONCENTRATIONS IN AMPHIBOLITE

Major and trace element concentrations in amphibolite determined by INAA. Oxides are given in wt%, trace elements in ppm.

Sample	Na ₂ O	K ₂ O	Sc	Cr	FeO	Co	La	Ce	Sm	Eu	Lu	Hf	Th
85-1	2.06	-	36.51	744	11.25	44.5	4.2	11.2	1.73	0.77	0.26	1.4	1.0
85-34	1.66	-	41.27	324	9.61	40.4	8.1	18.8	1.82	0.69	0.25	1.4	1.8
85-35	2.02	0.41	40.78	122	14.04	47.0	9.9	24.8	4.01	1.49	0.56	4.1	0.9
85-27	2.36	0.32	45.41	395	11.01	46.2	2.3	6.5	1.24	0.49	0.24	1.4	-
85-54	2.39	-	39.56	312	9.26	39.8	2.1	6.4	1.13	0.55	0.23	-	-
85-77D	1.63	0.37	29.90	38	11.97	42.5	7.5	20.5	3.08	0.91	0.17	1.2	1.6
85-81B	1.05	0.33	50.32	1455	9.62	44.6	9.7	25.1	1.95	0.69	0.29	1.7	2.2
85-92-1	1.58	0.46	33.38	673	8.49	37.4	1.6	5.2	0.92	0.63	0.17	-	-
85-100	1.29	0.39	43.52	84	13.80	54.0	2.5	7.1	1.47	0.69	0.29	-	-
86-23	1.85	-	37.00	975	9.18	39.2	2.2	7.0	1.33	0.45	0.26	-	-
86-33	1.59	-	56.80	202	13.33	56.9	1.4	-	1.14	0.50	-	-	-
86-25D	2.07	-	45.81	230	12.16	48.8	2.9	-	1.77	0.73	0.35	-	-
86-19	2.69	-	35.03	343	8.35	37.3	9.9	18.7	1.96	0.66	-	1.0	1.3

Trace element concentrations in amphibolite determined by XRF. Concentrations are given in ppm.

Sample	Ni	V	Ba	Rb	Sr	Zr	Y	Nb	Ga	Cu	Zn
86-23	144	183	36	4	208	35	10	-	13	-	96
86-33	84	248	11	5	71	30	12	1	16	82	87
86-19	147	166	91	4	195	53	11	1	15	52	54

TABLE XII

MAJOR AND TRACE ELEMENT CONCENTRATIONS IN
GROUP I METASOMATITE

Major and trace element concentrations in Group I metasomatite determined by INAA. Oxide concentrations are given in wt%; trace element concentrations are given in ppm.

Sample	Na ₂ O	K ₂ O	Sc	Cr	FeO	Co	La	Ce	Sm	Eu	Lu	Hf	Th
85-31A	1.51	0.29	33.79	917	12.31	55.4	4.1	12.3	1.36	1.43	0.22	1.0	-
86-25C	1.37	0.78	48.63	306	14.66	60.9	3.4	10.0	2.59	0.84	0.50	-	-
86-15	1.42	0.55	35.94	1240	9.61	51.0	6.9	17.8	2.02	0.63	0.28	1.1	1.2
86-16	1.39	-	49.21	686	10.63	54.8	6.7	20.0	2.24	0.69	0.29	-	-

Trace element concentrations in Group I metasomatite determined by XRF. Concentrations are given in ppm.

Sample	Ni	V	Ba	Rb	Sr	Zn	Y	Nb	Ga	Cu	Zn
86-15	225	163	104	8	47	38	13	1	13	32	77
86-16	226	217	85	6	30	34	15	1	15	185	61

TABLE XIII
MAJOR AND TRACE ELEMENT COMPOSITIONS IN
GROUP II METASOMATITE

Major and trace element concentrations in Group II metasomatite determined by INAA. Oxide concentrations are given in wt%; trace elements in ppm.

Sample	Na ₂ O	K ₂ O	Sc	Cr	FeO	Co	La	Ce	Sm	Eu	Lu	Hf	Th
85-30	1.46	0.31	42.63	417	13.44	52.8	5.4	16.0	2.32	1.17	0.27	3.0	0.8
85-28	1.56	0.39	58.92	128	16.11	66.5	5.7	12.7	2.42	1.24	0.44	2.4	1.5
85-67	1.11	-	32.79	1044	12.05	55.8	5.0	13.1	1.30	0.68	0.15	-	0.7
85-74A	1.40	0.29	42.02	506	13.99	71.4	4.2	13.2	3.76	2.43	0.46	2.9	-

TABLE XIV
MAJOR AND TRACE ELEMENT CONCENTRATIONS IN
GROUP A METAULTRAMAFIC ROCKS

Major and trace element concentrations in Group A metaultramafic rocks determined by INAA. Oxide concentrations are given in wt%; trace elements in ppm.

Sample	Na ₂ O	K ₂ O	Sc	Cr	FeO	Co	La	Ce	Sm	Eu	Lu	Hf	Th
85-32A	0.37	-	19.38	3224	13.58	87.2	1.9	8.3	0.66	0.14	0.14	-	0.66
85-32D	0.16	-	14.62	1306	12.44	82.0	1.2	4.4	0.37	0.07	0.10	0.6	0.42
85-87C	0.34	-	15.88	4097	14.00	93.0	4.2	30.0	1.06	0.48	0.25	-	1.73
85-88	0.43	-	14.53	3153	9.55	81.4	8.3	14.1	1.73	0.33	0.14	0.9	1.60
85-113	0.19	-	15.77	3205	10.84	96.1	6.1	17.2	1.09	0.29	0.14	-	0.95
85-111	0.31	-	12.56	429	7.74	64.5	10.1	18.2	1.71	0.40	0.16	-	2.20
85-112	0.17	-	15.49	3626	11.45	93.2	6.4	16.7	1.28	0.28	-	1.4	1.10

Trace element concentrations in Group A metaultramafic rocks determined by XRF. Concentrations are given in ppm.

Sample	Ni	V	Ba	Rb	Sr	Zn	Y	Nb	Ga	Cu	Zn
85-111	866	135	34	2	47	26	13	1	1	3	6
85-112	1354	107	14	2	23	30	10	2	5	21	123

TABLE XV

MAJOR AND TRACE ELEMENT CONCENTRATIONS IN
GROUP B METAULTRAMAFIC ROCKS

Major and trace element concentrations in Group B metaultramafic rocks determined by INAA. Oxide concentrations are given in wt%; trace elements in ppm.

Sample	Na ₂ O	K ₂ O	Sc	Cr	FeO	Co	La	Ce	Sm	Eu	Lu	Hf	Th
85-77A	1.01	0.17	22.69	3998	8.88	59.7	8.2	28.4	2.35	0.55	0.17	1.4	2.50
85-77B	0.82	0.22	20.53	1376	10.11	70.0	4.5	11.1	0.83	0.64	0.10	-	0.62
85-78	0.32	-	16.24	2499	11.72	93.5	4.6	11.4	1.04	0.37	0.17	0.9	0.82
85-82	0.48	-	14.72	2636	10.80	95.2	7.1	20.8	1.18	0.23	0.14	0.8	1.12
85-85	0.26	-	14.26	2431	11.24	73.0	5.4	11.0	1.36	0.19	0.13	1.1	1.20
86-25A	0.45	-	18.00	2261	13.39	99.9	6.6	14.9	1.13	0.30	-	-	0.90
86-25B	0.85	-	22.03	2220	12.27	83.8	7.2	14.5	1.41	0.39	0.28	1.0	1.30
86-10	0.53	0.35	21.36	2685	14.25	85.0	4.1	-	1.27	0.42	0.34	-	-

Trace element concentrations in Group B metaultramafic rocks determined by XRF. Concentrations are given in ppm.

Sample	Ni	V	Ba	Rb	Sr	Zn	Y	Nb	Ga	Cu	Zn
86-10	829	96	75	17	17	33	12	-	7	-	74

Figure 18. ACF diagram.

TABLE XVI
RATIOS OF SELECTED ELEMENTS
FOR EACH ROCK TYPE

<u>Sample</u>	<u>CaO/MgO</u>	<u>MgO/(MgO+FeO)</u>	<u>La/Sm</u>	<u>FeO/Sc</u>
AMPHIBOLITE				
85-1	N.A.	N.A.	2.43	0.31
85-34	1.27	0.50	4.45	0.23
85-35	1.61	0.32	2.47	0.34
85-27	N.A.	N.A.	1.85	0.24
85-54	N.A.	N.A.	1.86	0.23
85-77D	N.A.	N.A.	2.44	0.40
85-81B	N.A.	N.A.	4.97	0.19
85-92-1	N.A.	N.A.	1.74	0.25
85-100	N.A.	N.A.	1.70	0.32
86-23	1.33	0.52	1.65	0.25
86-33	1.46	0.42	1.23	0.23
86-25D	N.A.	N.A.	1.64	0.27
86-19	1.11	0.54	5.05	0.24
Average	<u>1.36</u>	<u>0.46</u>	<u>2.57</u>	<u>0.27</u>
GROUP I METASOMATITE				
85-31A	0.88	0.52	3.01	0.36
86-25C	N.A.	N.A.	1.31	0.30
86-15	0.65	0.64	3.42	0.27
86-16	0.68	0.61	2.99	0.22
Average	<u>0.74</u>	<u>0.59</u>	<u>2.68</u>	<u>0.29</u>
GROUP II METASOMATITE				
85-30	N.A.	N.A.	2.33	0.31
85-28	N.A.	N.A.	2.35	0.27
85-67	0.69	0.56	3.85	0.37
85-74A	N.A.	N.A.	1.12	0.33
Average	<u>0.69</u>	<u>0.56</u>	<u>2.41</u>	<u>0.32</u>
GROUP A METAULTRAMAFIC				
85-32A	0.19	0.62	2.88	0.70
85-32D	0.11	0.65	3.24	0.85
85-87C	N.A.	N.A.	3.96	0.88
85-88	N.A.	N.A.	4.80	0.66
85-113	0.19	0.70	5.60	0.69
85-111	0.33	0.78	5.91	0.62
85-112	0.13	0.75	5.00	0.74
Average	<u>0.19</u>	<u>0.70</u>	<u>4.48</u>	<u>0.73</u>

TABLE XVI
RATIOS OF SELECTED ELEMENTS
FOR EACH ROCK TYPE
(continued)

GROUP B METAULTRAMAFIC

85-77A	N.A.	N.A.	3.49	0.39
85-77B	N.A.	N.A.	5.42	0.49
85-78	0.30	0.66	4.42	0.72
85-82	0.21	0.69	6.02	0.73
85-85	0.17	0.69	3.97	0.79
86-25A	N.A.	N.A.	5.84	0.74
86-25B	N.A.	N.A.	5.11	0.55
86-10	0.27	0.65	3.23	0.67
Average	<u>0.24</u>	<u>0.67</u>	<u>4.68</u>	<u>0.64</u>

Amphibolite

Major element oxide and trace element concentrations for samples of amphibolite are shown in Tables VI and XI, respectively. The average concentrations and standard deviations of major element oxides and trace elements are shown in Tables XVII and XVIII. The bulk composition of the amphibolite is relatively uniform, as indicated by the relatively low standard deviations.

Metasomatite

Hornblende metasomatic rocks may be divided into two groups on the basis of field relationships (see above). Group I metasomatites are those that occur at concordant contacts between amphibolite and metaultramafic bodies and generally lack evidence of shearing. Group II metasomatites are those that occur within discordant contacts between amphibolite and metaultramafic bodies that are characterized by shears. The first group is always in direct contact with metaultramafic bodies and amphibolite. The second group may occur as shears through amphibolite, or along boundaries between amphibolite and metaultramafic bodies where shearing is evident.

Major element oxide and trace element concentrations for Group I metasomatites are shown in Tables VII and XII, and for Group II metasomatites in Tables VIII and XIII. Average concentrations and standard deviations of major

element oxides and trace elements are shown in Tables XVII and XVIII. These two groups are not readily separable geochemically on the basis of statistical analysis.

Figure 19 shows the average concentrations of major element oxides and trace elements for Group I and Group II metasomatites relative to amphibolite. In Group I, concentrations are significantly higher for K_2O and Cr, and lower for Eu and Hf relative to Group II. Figure 20 is a diagram of the relative standard deviations for trace elements in Group I and Group II metasomatites and amphibolite. Group II metasomatites commonly have a higher standard deviation for most trace elements than Group I, but have significantly lower standard deviations for La, Ce, and K_2O .

Figure 21 is a chondrite-normalized REE plot showing average amphibolite, Group I metasomatite, and Group II metasomatite. Average Group I metasomatite plots parallel to average amphibolite, but shows overall higher REE concentrations. Eu has a slightly higher positive anomaly than amphibolite. The average concentrations of La and Ce in Group II metasomatite and amphibolite are not statistically distinct. Group II contains higher concentrations in Sm, Eu, and Lu than Group I and has a stronger positive Eu anomaly.

Two of the lenses that contain the distinct mineral assemblages discussed above occur within Group II

Figure 19. Trace element diagram for average concentrations in Group I and II metasomatites relative to average concentrations in amphibolite.

Figure 20. Relative standard deviation for average trace element concentrations in amphibolite and Group I and II metasomatites.

Figure 21. Chondrite-normalized REE plot of average concentrations of rare earth elements in amphibolite and Group I and II metasediments.

metasomatic rocks. Samples from these lenses were analyzed for trace element compositions. One contains the assemblage phlogopite-hornblende-hypersthene+apatite+ opaques (sample no. 85-116b), and the other contains the assemblage Mg-hornblende-cummingtonite (sample no. 85-29). The trace element concentrations for these samples are shown in Table IXX.

Figure 22 shows the trace element concentrations within the phlogopite-hornblende sample relative to average amphibolite. This diagram indicates that this rock is significantly depleted in Na_2O , Lu, and Th, but is highly enriched in most other trace elements relative to amphibolite. K_2O , Cr, LREE, and Eu are highly enriched while HREE are below the detectability limits for INAA. The two generally incompatible elements K_2O and Cr are both enriched. This sample contains appreciable concentrations of Cs, Ba, Rb, and Zn, which are not detectable in amphibolite or metasomatite (Table IXX).

Metaultramafic Rocks

The metaultramafic rocks may be separated into two groups on the basis of mineralogy. Group A metaultramafic rocks contain a high modal abundance of orthopyroxene, and Group B contains a high modal abundance of Mg-hornblende. Cluster analysis of the geochemical compositions of the metaultramafic rocks corroborate this division to a large extent (Figure 23). These two groups loosely define

TABLE XIX

MAJOR AND TRACE ELEMENT CONCENTRATIONS DETERMINED BY INAA
FOR SAMPLES OF A HORNBLENDE-PHLOGOPITE LENS (85-116B)
AND A Mg-HORNBLENDE-CUMMINGTONITE LENS (85-29)

<u>Sample</u>	<u>Na₂O</u>	<u>K₂O</u>	<u>Sc</u>	<u>Cr</u>	<u>FeO</u>	<u>Co</u>	<u>La</u>	<u>Ce</u>	<u>Sm</u>	<u>Eu</u>	<u>Lu</u>
85-116B	1.07	2.10	63.40	2249	19.49	121.8	22.6	47.0	6.93	2.26	-
85-29	0.64	0.13	11.75	2451	7.56	64.3	1.2	5.8	0.79	0.34	0.11

<u>Sample</u>	<u>Hf</u>	<u>Th</u>	<u>Zn</u>	<u>Rb</u>	<u>Cs</u>	<u>Ba</u>
85-116B	2.0	-	360	150	8.0	1200
85-29	-	-	-	-	-	-

1. Oxides are given in wt%, trace elements in ppm.

Figure 22. Trace element diagram for concentrations in a hornblende-phlogopite lens (sample 85-116B) relative to average concentrations in amphibolite.

Figure 23. Dendrogram from a cluster analysis of metaultramafic rocks. The x-axis represents similarities, with greater differences between samples to the left.

"least altered" (Group A) and "altered" (Group B) metaultramafic rocks. No entirely unaltered metaultramafic rocks were found in this study. Group A rocks are less metasomatically altered than Group B rocks.

Major element oxide and trace element concentrations for Group A metaultramafic rocks are shown in Tables IX and XIV, and for Group B in Tables X and XV. Average major element oxide and trace element concentrations and their standard deviations are shown in Tables XVII and XVIII.

Figure 24 is a plot of the concentration of selected major and trace elements for the average Group B metaultramafic rocks relative to Group A. The plot shows that Group B metaultramafic rocks are similar in trace element composition relative to Group A except for Na_2O and K_2O , which are highly enriched in Group B. Sc is also somewhat enriched in Group B relative to Group A metaultramafic rocks.

Figure 25 is a chondrite-normalized REE plot of average Group A and Group B metaultramafic rocks and average amphibolite. The metaultramafic rocks are enriched in LREE relative to amphibolite but have lower concentrations in other REE. Group A has a lower concentration of REE and has a larger negative Eu anomaly than Group B.

Figure 24. Trace element diagram for average concentrations in Group A metaultramafic rocks relative to average concentrations in Group B metaultramafic rocks.

Figure 25. Chondrite-normalized REE plot of average concentrations of rare earth elements in amphibolite and Group A and B metaultramafic rocks.

Autoradiography

Neutron activation autoradiography (NAAR) is a method by which the distribution of elements in a thin section of a rock may be observed (Beeson and Beeson, 1980).

Selected thin sections of samples from amphibolite, metasomatite, and metaultramafic rocks were analyzed in order to 1) determine if relic textures could be observed in metasomatic rocks that are not observed petrographically, 2) relate element distribution to the metasomatic process, and 3) aid in the identification of certain minerals. No relic textures were observed in these rocks. The element distributions are useful in differentiating metasomatic process and as an aid in mineral identification.

Figure 26 shows three autoradiographs from samples of amphibolite, Group I metasomatite, and Group A metaultramafic exposed seven days after irradiation. Figure 27 shows autoradiographs of the same samples exposed 32 days after irradiation. Table XX lists the most active elements during these exposures. There is little difference between the two exposures for each sample. Hornblende and plagioclase are easily distinguishable in the autoradiograph of amphibolite (Figure 26a and 27a). The hornblende (gray) contains most of the detectable trace elements, and plagioclase (black) displays little to no activity. In the autoradiograph of

A

B

C

Figure 26. Autoradiographs of amphibolite (a), metasomatite (b), and metaultramafic rock (c) exposed 7 days after irradiation.

A **B** **C**

Figure 27. Autoradiographs of amphibolite (a), metasomatite (b), and metaultramafic rock (c) exposed 32 days after irradiation.

TABLE XX

MOST ACTIVE ELEMENTS FOR EACH NAAR EXPOSURE,
LISTED IN DECREASING NET COUNTS

<u>Sample</u>	<u>Time of exposure after irradiation</u>	<u>Most active elements</u>
85-34	7 days	Na, Sc, Sm, La, Fe
85-34	32 days	Sc, Fe, Co, Eu
85-31A	7 days	Na, Sc, Sm, La, Fe
85-31A	32 days	Sc, Fe, Co, Eu
85-32A	7 days	Na, Cr, Sc, Fe, Sm, La
85-32A	32 days	Sc, Fe, Co
85-35	30 min	Mn
85-38	30 min	Mn

the metasomatic rock (Figure 26b and 27b)) the trace elements are homogeneously distributed and the grain boundaries of hornblende are indistinguishable. Bright spots in amphibolite and metasomatite autoradiographs are apatite grains in which REE are concentrated.

Figures 26c and 27c are autoradiographs of a Group I metasomatite. Dark areas are orthopyroxene porphyroblasts and Mg-chlorite-orthopyroxene assemblages, and the gray areas correspond to Mg-hornblende, which show the higher concentration of detectable trace elements. Bright spots in the autoradiograph correspond to spinel and sulfide grains in which Cr, Fe, and Co are concentrated.

Figure 26a indicates that plagioclase contains little Na. This exposure was completed when the main activity in the sample would be due to Na in plagioclase if present. This is consistent with optical determinations of anorthite compositions in plagioclase near An₈₀. The other Na-bearing phase would be hornblende. However, the hornblende in these rocks are probably low in Al and thus would contain very little Na in the amphibole A-site.

Figure 28 is an autoradiograph exposed 30 minutes after irradiation of an amphibolite that contains garnet. Figure 29 is an autoradiograph exposed 30 minutes after irradiation of a hornblende-garnet lens. The element producing the most activity at the time was Mn, which is concentrated in garnet, resulting in bright spots. The

Figure 28. Autoradiograph of a garnet-bearing amphibolite exposed 30 min. after irradiation.

Figure 29. Autoradiograph of a garnet lens exposed 30 min. after irradiation.

concentration of Mn in garnet may indicate that the garnet is in the pyralspite group.

Gains and Losses

Metasomatism may be characterized by the mass gain and loss of chemical components. Isocon diagrams constructed after the method of Grant (1986) are used to determine the percent mass gain and loss in an altered rock relative to less altered or unaltered rock and the element mobility during metasomatism.

Variables used in the following equations are listed in Table XXI. An isocon line is a line of constant slope on a plot of C^A vs. C^O . The isocon is determined by a set of elements for which the ratio C^A/C^O is equal. These elements are interpreted to be immobile during the alteration of the rock. Also plotted on the diagram are lines for constant mass and constant volume. The slope of the line on the diagram for constant mass is one, which would be the case for alteration without a gain or loss in mass. The slope of the constant volume line is equal to the ratio of the specific gravity in unaltered rock to that in the altered rock. Constant volume would indicate that there was no change in volume during alteration and that the density change was due entirely to a mass change. An isocon that does not fall on either the constant mass or the constant volume lines indicates a change in both mass and volume. The change in mass is then given by the

TABLE XXI
VARIABLES USED IN THE DISCUSSION OF
THE ISOCON METHOD OF
GRANT (1986)

<u>Variable</u>	<u>Description</u>
C^O	Concentration of a component in the unaltered rock used to define an isocon line
C^A	Concentration of a component in the altered rock used to define an isocon line
C_i^O	Concentration of a component, i, in the unaltered rock
C_i^A	Concentration of a component, i, in the altered rock
ΔC_i	Change in the concentration of component i due to alteration
ΔM	Change in mass
ΔV	Change in volume
ρ^O	Density of the unaltered rock
ρ^A	Density of the altered rock

equation

$$\Delta M = C^O / C^A - 1,$$

and a change in volume by the equation

$$\Delta V = (C^O / C^A)(\rho^A / \rho^O) - 1.$$

The elements that plot above the isocon line in the diagram have been gained by the rock during alteration, and those plotting below the isocon line have been lost. The percent of the mass gain or loss of the elements is given by the equation

$$\Delta C_i / C_i^O = [(C^O / C^A)(C_i^A / C_i^O) - 1] \times 100.$$

The specific gravity for selected samples of amphibolite, metasomatite, and metaultramafic rocks in the Branham Lakes area are presented in Table XXII. The average specific gravity is 2.99 for amphibolite, 3.11 for Group I metasomatite, 3.11 for Group II metasomatite, 3.14 for Group A metaultramafic rocks, and 3.10 for Group B metaultramafic rocks. This indicates that there was a mass and/or volume change in these rocks due to metasomatism.

Figure 30 is an isocon diagram of average unaltered amphibolite plotted against average Group I metasomatite. Lines for constant mass and constant volume are also shown. An isocon can be defined by those components, Zr, CaO, Ga, V, and TiO₂, believed to be immobile during metasomatism, indicating an overall mass gain of +9% and volume gain of +4.6%. The mass gains and losses of each

TABLE XXII
SPECIFIC GRAVITY OF SELECTED SAMPLES
OF EACH ROCK TYPE

<u>Sample</u>	<u>Specific gravity</u>
AMPHIBOLITE	
85-1	2.97
85-34	3.00
86-19	2.96
86-23	2.98
86-25D	3.00
86-33	3.02
GROUP I METASOMATITE	
85-31A	3.13
86-13	3.15
86-15	3.06
86-16	3.10
86-25C	3.11
GROUP II METASOMATITE	
85-28	3.14
85-30	3.14
85-67	3.08
GROUP A METAULTRAMAFIC	
85-32A	3.13
85-32C	3.12
85-32D	3.20
85-88	3.07
85-111	3.07
85-112	3.22
85-113	3.20
GROUP B METAULTRAMAFIC	
85-39	3.09
85-41	3.16
85-85	3.00
86-10	3.13
86-25A	3.14
86-25B	3.11

Figure 30. Isocon diagram of average concentrations of components in unaltered amphibolite vs. average concentrations in Group I metasomatite.

component are shown in Table XXIII, and displayed graphically in Figure 33.

Figure 31 is an isocon diagram of average amphibolite plotted against average Group II metasomatite. An isocon can be defined by the components K_2O , MnO , Ce , Na_2O , and TiO_2 , indicating an overall mass gain of +12% and volume gain of +7.5%. Mass gains and losses for the components are shown in Table XXIII and Figure 33.

Figure 32 is an isocon diagram of average Group A metaultramafic rocks plotted against average Group B metaultramafic rocks. Group A metaultramafic rocks are not entirely unaltered and the percent gains and losses are not total, but are relative to the least altered metaultramafic rocks. An isocon can be defined by the components Zr , Zn , Lu , Hf , Al_2O_3 , La , TiO_2 , and MnO , indicating an overall mass loss of -8% and a volume loss of -7% from least altered to most altered metaultramafic. Mass gains and losses for components are shown in Table XXIII and Figure 33.

As shown in Figure 33, metasomatic rocks show mass losses for the components Al_2O_3 , CaO , Na , and Th , and mass gains for the components Fe , Mg , Cr , and Co relative to amphibolite. The most altered metaultramafic rocks show mass losses for the components Fe , Mg , Cr , Co , and Th and mass gains for the components Al_2O_3 , CaO , and Na relative to the least altered metaultramafic rocks.

TABLE XXIII
PERCENT MASS GAINS AND LOSSES FOR
MAFIC AND ULTRAMAFIC
BULK COMPOSITIONS

<u>Element</u>	<u>MAFIC</u>		<u>ULTRAMAFIC</u>
	<u>Group I</u>	<u>Group II</u>	<u>Group B</u>
SiO ₂	+7%	+16%	-11%
Al ₂ O ₃	-19	-34	0
TiO ₂	-1	+4	-2
FeO	+9	+44	-6
MnO	+29	0	-2
CaO	0	-6	+9
MgO	+85	+81	-12
K ₂ O	+37	0	+22
Na ₂ O	-16	-14	+94
P ₂ O ₅	+10	+118	+80
Sc	+11	+21	+11
Cr	+71	+37	-15
Co	+34	+62	-11
La	+17	+12	0
Ce	+21	+5	-6
Sm	+26	+53	+8
Eu	+45	+104	+28
Lu	+21	+40	-8
Hf	+20	+72	-1
Th	-25	-15	-11
Ni	+96		-31
V	+4		-28
Ba	+123		+186
Rb	+78		+680
Sr	-74		-55
Zr	0		+8
Y	+38		-5
Nb	+9		-
Ga	+4		+114
Cu	+76		-
Zn	-5		+1

Figure 31. Isocon diagram of average concentrations of components in unaltered amphibolite vs. average concentrations in Group II metasomatite.

Figure 32. Isocon diagram of average concentrations of components in Group A metaultramafic rocks vs. average concentrations in Group B metaultramafic rocks.

Figure 33. Graph of percent mass gains or losses of componentets in each altered rock type.

Metasomatic rocks show a mass gain for all REE relative to amphibolite. Metaultramafic rocks show a slight loss only for Ce, but show mass gains in most other REE. K_2O shows a large mass gain in Group I metasomatite and metaultramafic rocks, but very little mass gain in Group II metasomatite.

DISCUSSION

Thompson (1959), Korzhinskii (1965, 1970), Vidale (1969), Vidale and Hewitt (1973), Fisher (1973, 1975), Frantz and Mao (1976), Joesten (1977), and Brady (1977) were principal in the development of the theoretical basis for metasomatic reactions between contrasting bulk compositions during moderate to high grade metamorphism. The fluid phase plays an important role in the metasomatic process (Vidale and Hewitt, 1973). On the basis of phase rule considerations, Korzhinskii (1965), Vidale (1969), and Vidale and Hewitt (1973) determined that the metasomatic assemblages developed as one and two solid phase assemblages in local equilibrium with the fluid phase. Korzhinskii (1965) showed that the Gibbs phase rule, $f = c - p + 2$, may be reformulated to $f = c - p + 2 - m$, where f = variance, c = total number of independent components, p = number of coexisting phases, and m = number of chemical components whose chemical potentials are externally controlled (mobile components). The variance is decreased by m , the number of fixed intensive variables. Over a range of pressure, temperature and other intensive variables, $p \leq c - m$. Therefore, metasomatic assemblages characteristically contain fewer solid phases

than the reacting bulk compositions.

Two types of chemical components were defined by Korzhinskii (1970) for the study of metasomatic processes. The concentration of immobile (or inert) components is constant in a rock throughout metasomatism. Thus the concentration of the immobile components in an altered rock is dependant on their concentration in the original rock. The concentration of mobile components in an altered rock may be sharply changed relative to the original rock. Mobile components move in response to chemical potential gradients between two contrasting bulk compositions through a fluid phase (Vidale and Hewitt, 1973). A quantitative discussion of the diffusion of chemical components through an intergranular fluid during metamorphic differentiation using nonequilibrium thermodynamics is given by Fisher (1973). Joesten (1977) discussed the quantification of mineral assemblage zoning due to diffusion metasomatism during metamorphism.

Brady (1977) discussed diffusion-dominated metasomatism at contacts between ultramafic bodies and pelitic schist in two temperature regimes. In the lower temperature regime, the sequence serpentinite | talc-magnesite | talc | chlorite | pelitic schist is observed, and at higher temperatures the sequence serpentinite | talc-magnesite | talc | actinolite | biotite | pelitic schist is observed. The chemical components that were mobile at the

lower temperature include SiO_2 , MgO , FeO , and MnO . In the higher temperature system, CaO became an additional mobile component, resulting in the crystallization of actinolite. Sanford (1982) discussed diffusion-controlled metasomatism between ultramafic rocks and country rocks of variable composition and metamorphic grade in an Ordovician metamorphic sequence in Vermont and Massachusetts. A generalized sequence of metasomatic zones for these rocks is ultramafic rock|talc-carbonate|talc|Ca-amphibole-chlorite|chlorite|transitional country rock|country rock. Other similar metasomatic sequences between ultramafic rocks and country rocks have been described by Fowler and others (1981), Scotford and Williams (1983), and Crewe (1985).

Desmaris (1981) described ultramafic bodies in the Ruby Range, approximately 50 km southwest of the Tobacco Root Mountains, that contain mono- or biminerally metasomatic rocks at the contacts between these bodies and the country rock consisting of felsic and mafic gneisses. A generalized sequence of the metasomatic zones is ultramafic rock|anthophyllite|hornblende or gedrite|biotite|country rock. The ultramafic bodies are interpreted to have participated in the same deformation and metamorphism experienced by the country rocks. The metamorphism was in the upper amphibolite facies, and various equilibria in the rocks indicate conditions of

metamorphism were approximately 710° C and 5 kbar pressure. It is unclear whether the ultramafic rocks were emplaced as igneous intrusions prior to metamorphism and tectonism, or if tectonism and metamorphism accompanied their emplacement as cold ultramafic bodies (Desmaris, 1981).

The metasomatic rocks that have developed between the amphibolite and metaultramafic rocks in the Branham Lakes area of the southern Tobacco Root Mountains have been metamorphosed under the conditions of the upper amphibolite facies of regional metamorphism. In this discussion, 1) the structural relations between the amphibolite unit and surrounding units will be examined in order to relate the amphibolite unit to the regional geology of the Tobacco Root Mountains, 2) the metamorphic mineral assemblages in the amphibolite, metasomatite, and metaultramafic rocks will be examined in order to determine the contemporary assemblages in each bulk composition, 3) the conditions of metamorphism will be established, and 4) the element mobility during metasomatism between mafic and ultramafic rocks under these conditions will be examined.

The Archean terrane of southwestern Montana is recognized as containing contrasting metamorphic and structural domains that are juxtaposed across zones of deformation. Such relations have been observed by Salt

and Mogk (1986) in the Spanish Peaks area of the Madison Range, southwest Montana. It is therefore important to briefly establish the general structural relations and time of metamorphism of rocks in the Branham Lakes cirque.

The amphibolite unit (Aa), which contains the metaultramafic bodies (Amu), is considered to be a single block separated from other lithologic groups by structural boundaries and intrusive contacts. The common histories of the different lithologic associations can be examined in light of 1) orientation of compositional layering within in the units, 2) overall mineral textures and fabrics, 3) metamorphic assemblages, and 4) presence of relic-primary or primary textures in the rocks.

Figure 13 shows pi plots of the orientations of compositional layering within the three lithologic groups. The orientations of compositional layering in the amphibolite and in the interlayered sequence cropping out on the north wall of the cirque are generally similar, but are discordant to the orientation of compositional layering in the interlayered sequence in the southern portion of the cirque. The amphibolite unit is separated from the interlayered sequence to the south by a large shear zone that is characterized by tectonite fabrics. This shear zone is at least 100 meters wide and the internal fabric is oriented similarly to that of the amphibolite unit. It is possible that the compositional

layers measured in the interlayered sequence in the south part of the area is a tectonic block within the shear zone. The amphibolite unit is separated from the interlayered sequence to the north by what is interpreted to be an imbricate fault system (Plate 1). The overall mineral textures within the three units are similar in that they are granoblastic and any foliation is weakly developed.

Although an exhaustive study of metamorphic mineral associations in all lithologic groups has not been attempted, there is presently no data to indicate that metamorphic mineral assemblages formed under significantly different metamorphic conditions. The metamorphic mineral assemblage data and textures in various ages of shear zones and lithologic units indicates structural juxtaposition prior to the peak conditions of metamorphism.

The units that contain relic primary igneous textures and primary igneous textures are the layered mafic intrusion and the Tobacco Root Batholith, respectively. Both units are interpreted as post peak metamorphism. The layered mafic intrusion locally produces a cordierite hornfels within the quartzite and interlayered metapelites near the crest of Bradley Peak on the northeast wall of the cirque, and truncates the shear zone that separates the amphibolite unit from the interlayered sequence to the

south. The Tobacco Root Batholith and related satellite intrusive bodies are unmetamorphosed and intrude all other lithologic groups. Intrusive breccia is locally developed and contains clasts of the other lithologic groups. Recrystallization of country rocks occurs locally along the margin of the intrusions.

The metamorphic mineral assemblages reflect the conditions of metamorphism. In order to determine the metamorphic conditions and the metamorphic history, the mineral assemblages in the different bulk compositions must be correlated to each other. The conditions of metamorphism and the metamorphic history can then be constructed.

The amphibolite unit contains amphibolite (Aa) and metaultramafic bodies (Amu). These two rock types are mafic and ultramafic bulk compositions, respectively. This is illustrated by the ACF diagram (Figure 18). Polymetamorphism and metasomatism of these rock types resulted in a variety of mineral assemblages. Three groups of time-equivalent mineral assemblages can be deduced from textural relationships of the minerals and field relationships of the rocks: 1) relic mineral assemblages, 2) regional metamorphic and metasomatic mineral assemblages and 3) retrograde metamorphic, or later regional metamorphic, mineral assemblages. Figure 34 summarizes these three groups on the basis of the mafic

Figure 34. Time relationships of mineral assemblages in mafic and ultramafic bulk compositions.

and ultramafic bulk compositions.

The oldest mineral assemblages occur in rocks of ultramafic composition and include ol-opx-chrom, ol-chrom, and opx-chrom (Table III). The fractured and replaced textures in the olivine and orthopyroxene indicate a lack of textural equilibrium with the Mg-hornblende-bearing mineral assemblages that occur in shears and fractures cross-cutting bronzite and olivine porphyroclasts. Thus the olivine and bronzite are assigned to an earlier time of crystallization than the Mg-hornblende. There are no recognized mineral assemblages of equivalent age in the amphibolite.

The assemblage ol-opx-chrom is common in igneous rocks of ultramafic composition. However, it is not clear whether the mineral assemblages in these rocks are relic igneous or were crystallized in an earlier high-grade metamorphism. An earlier high-grade gneissic terrain in the northeastern part of the Tobacco Root Mountains that developed prior to the amphibolite grade metamorphic event ca. 2750 m.y. ago was suggested by Hanley and Vitaliano (1983). However, a relationship between the earliest assemblages in the rocks of ultramafic composition in the Branham Lakes area and this earlier gneissic terrain has not been established. Metamorphosed ultramafic rocks within gneiss in the Ruby Range have been interpreted to have been emplaced either 1) as intrusions prior to peak

amphibolite grade metamorphism, or 2) as cold ultramafic bodies during the metamorphism and tectonism (Desmarais, 1981).

The earliest mineral assemblage occurring in rocks of mafic composition is hbl-pc-ap-qtz $\pm$ op, which defines the amphibolite. If an earlier metamorphic mineral assemblage had existed in these rocks, it was destroyed by recrystallization, thus the question mark in Figure 34.

Hornblende-rich metasomatite occurring at concordant contacts between amphibolite and metaultramafic bodies is gradational into the amphibolite. The mineral assemblages occurring in amphibolite and metasomatite are similar. Approximately equal modal abundances of apatite occur in both amphibolite and metasomatite. The main difference between amphibolite and metasomatite is the modal abundance of hornblende relative to plagioclase. The type of garnet occurring in amphibolite and metasomatite may be similar, as determined by autoradiography. These relationships indicate that the mineral assemblages in the amphibolite and hornblende metasomatite crystallized under the same conditions and during the same metamorphic event.

Since hornblende metasomatite also occurs in shears cross-cutting amphibolite, and contains the same mineral assemblages as metasomatite that is gradational into amphibolite, it is interpreted also to be time-equivalent to the crystallization of amphibolite. The kinematic

behavior within the shear zones is suggested by the lenses containing unique mineral assemblages and compositions that occur in these shears. The assemblages include garnet-hornblende and phlogopite-hornblende lenses. During shearing, areas within a shear zone may dilate, allowing the precipitation of minerals from the fluid phase into the areas as they dilate. This would result in mineral assemblages with compositions reflecting the chemistry of the fluid phase. The mineral textures and assemblages in these lenses are similar to those in the metasomatite and amphibolite. The mineral assemblages in these dilatant zones are interpreted to be time equivalent to the crystallization of amphibolite. The data indicate that shearing was concurrent with metasomatism, but that the main recrystallization continued after shearing had ceased.

The metaultramafic bodies are truncated by the same shears that contain hornblende metasomatite within the amphibolite. Therefore, the ultramafic bodies were present at the time of shearing and experienced the same metamorphic history as the amphibolite and metasomatite.

The metasomatic assemblages containing Mg-hornblende occur in shears that cut the metaultramafic bodies. These shears may have been activated due to different physical properties of the metaultramafic rocks and the amphibolite during deformation. The shears cutting the metaultramafic

bodies allowed metasomatizing fluids to infiltrate through the ultramafic rocks to produce the Mg-hornblende-bearing mineral assemblages.

The assemblages in amphibolite and metasomatic rocks (Table III) are indicative of the amphibolite facies of metamorphism. The anorthite content of plagioclase has been shown to increase with increasing metamorphic grade in amphibolite from albite (An0-10) in lower grade rocks to bytownite (An70-90) in higher grade rocks (Winkler, 1979). The anorthite content of amphibolite in the study area was determined to be approximately An80, indicating that these rocks formed under high temperatures. The tentative identification of pyralspite garnet in the amphibolite and metasomatite suggests that high pressures may have also played a role (Winkler, 1979).

The conditions during the peak of metamorphism in the Branham Lakes cirque have been established from the mineral assemblages. Within the Tobacco Root Mountains, Immega and Klein (1976), studying metairon formations, reported conditions of metamorphism in the range 650-750° C and 4-6 kb pressure approximately 2 km to the south of the study area. Friberg (1976) reported that the sillimanite-orthoclase isograd had been exceeded approximately 5-10 km north of the study area in the Spuhler Peak area and estimated conditions of metamorphism to be in the range 600-800° C and 4-6 Kbar pressure.

These conditions are consistent with the conditions of the upper amphibolite facies as shown in Winkler (1979, p. 65) where the pressures of the solid and fluid phases are equal. Therefore, the amphibolite and metasomatic rocks in the study area are interpreted to have been crystallized under these conditions. The age of the amphibolite grade metamorphism has been determined on the basis of Rb/Sr systematics on gneiss in the Tobacco Root Mountains by Mueller and Cordua (1976). They report an age of 2667 ± 66 m.y.

The metamorphic conditions that developed in the rocks after the peak of metamorphism are indicated by mineral assemblages that are developed locally within all bulk compositions. In these locally developed assemblages, the phase relations are determined from reaction rims and coronas that separate pre-existing minerals, pseudomorphs, and mineral patches. The small volume of these assemblages attest to the generally dehydrated character of the bulk compositions after the peak of metamorphism.

The mineral assemblage Mg-chlorite-orthopyroxene-green spinel occurs locally within metaultramafic rocks. The assemblage is consistent with the conditions of the amphibolite facies (Winkler, 1979; Evans, 1977) and those reported by Immege and Klein (1976) and Friberg (1976). However, the occurrence of orthopyroxene rimming

Mg-hornblende, thus separating Mg-hornblende from Mg-chlorite, suggests that the mineral assemblage crystallized later than the Mg-hornblende.

Reaction assemblages occurring in these rocks include symplectite rims of pc-opx rimming garnet, separating the garnet from hornblende, and local pseudomorphic replacement of hornblende by biotite-orthopyroxene-plagioclase-sillimanite(?) or muscovite(?)-opaque. The occurrence of these assemblages indicates a change in the conditions of these rocks resulting in disequilibrium between some mineral species, particularly garnet and hornblende.

The textures of the symplectite rim around garnet are similar mineralogically and texturally to those described by Wilkerson and others (1988). They interpreted these coronas to be in response to reheating and hydration of a high pressure (15 kb and 8 kb) metamorphic mineral assemblage at amphibolite facies conditions (3.5-5 kb).

Giletti (1966) reported a thermal event ca. 1700 m.y. ago that reached the almandine-amphibolite facies rank of metamorphism. The occurrence of clinozoisite in amphibolite is indicative of medium-grade metamorphism of mafic rocks (Winkler, 1979), thus records a post peak metamorphism in the Branham Lakes cirque at a lower grade of metamorphism. A later retrograde event of the greenschist facies affected rocks locally in the Tobacco

Root Mountains (Vitaliano and others, 1979). Friberg (1976) reported the conditions of the retrograde event to be approximately 450° C and 2 kb pressure.

A possible metamorphic history of the area may be drawn from this discussion:

1) Juxtaposition of the amphibolite unit and interlayered sequences on the north wall of the cirque by what is interpreted to be an imbricate fault system, and of the amphibolite unit and interlayered sequences in the southern part of the area across a major ductile shear zone;

2) Peak metamorphism in the upper amphibolite facies accompanied by metasomatism and shearing, resulting in amphibolite and metasomatic mineral assemblages in mafic and ultramafic bulk compositions;

3) Post peak metamorphism at possibly still high temperature, but lower pressure, resulting in reaction assemblages that include reaction rims, symplectite coronas, and mineral patches in each bulk composition;

4) Intrusion of the layered mafic intrusion into amphibolite and interlayered rocks and possible later metamorphic events at low grade conditions;

5) Intrusion of the Tobacco Root Batholith and related satellite intrusions into all other lithologic groups.

The occurrence of monomineralic mineral assemblages separating mafic and ultramafic bulk compositions indicates that metasomatism has taken place between the two contrasting bulk compositions. These monomineralic assemblages also occur in shears cutting the amphibolite and metaultramafic rocks. Two basic types of relationships for metasomatic rocks have been established: 1) those where the metasomatic rocks occur between a metaultramafic body and amphibolite at concordant contacts and have a gradational contact with the amphibolite, and 2) those where the metasomatite occurs in shears cutting the amphibolite and metaultramafic bodies. The first type of metasomatic rocks (Group I metasomatite) formed by diffusion of elements between a metaultramafic body and the amphibolite. The second type of metasomatic rocks (Group II metasomatite and Group B metaultramafic) formed by infiltration of elements in a fluid phase through shear zones.

Figure 20b shows the relative standard deviation for Group I and Group II metasomatites and amphibolite. Group I metasomatites show a relatively low standard deviation. This would be expected if diffusion-dominated processes develop in a stepwise fashion as shown by Korzhinskii (1965). The chemical composition of metasomatite throughout the metasomatic band and from band to band would be similar. Thus the standard deviation for each

element determined by averaging a number of samples across bands and from spatially separate bands would be low. In contrast, infiltration-dominated processes develop metasomatic fronts in which the chemical composition of the metasomatic rock is dependent on the composition of the fluid phase, which, in turn, is dependent on the composition of the wallrock (Korzhinskii, 1970).

Therefore, the variations in the composition of Group II metasomatites may be more dependent on the variations in the metamorphic processes and bulk composition along the shear zones. The standard deviation for Group II metasomatites generally follows the standard deviation for amphibolite, while Group I metasomatites generally have lower standard deviations than amphibolite, supporting this argument.

Figure 33 shows the percent gains and losses resulting from diffusion- and infiltration-dominated metasomatism of mafic and ultramafic bulk compositions under the conditions of the upper amphibolite facies. The figure shows that during diffusion-controlled metasomatism of amphibolite (Group I), the elements MgO, Cr, Co, K₂O, MnO, Sc, Hf and REE were gained, and Al₂O₃, Na₂O, and Th were lost. Figure 30 shows that Ba, Cu, Rb, Y, and Ni were gained and Sr was lost as well. The relatively immobile elements in this system are those that define the isocon line in Figure 30. These are Nb, Zr, P₂O₅, Zn,

CaO, Ga, V, TiO_2 and SiO_2 .

The immobile elements in the infiltration-dominated system (Group II) are those that define the isocon line in Figure 31. These are K_2O , MnO, Ce, and TiO_2 . Elements that were gained are SiO_2 , MgO, P_2O_5 , Sc, Cr, FeO, Co, Hf, La, Sm, Eu, and Lu. Elements that were lost are Al_2O_3 , CaO, Na_2O , and Th. Figure 33 shows the percent gains and losses of these elements in the infiltration-dominated system.

Lenses that occur in shears cutting amphibolite contain distinct compositions. Figure 22 is a diagram showing the concentration of a phlogopite-hornblende lens relative to amphibolite. This lens shows a depletion in Na_2O , Lu, and Th relative to amphibolite. It is enriched in Sc, Fe, Co, and Hf and highly enriched in K, Cr, La, Ce, Sm, and Eu relative to amphibolite. The lens also contains high concentrations of the incompatible elements Cs, Ba, and Rb. The enrichment in Cs, Ba, Rb, and K_2O in these lenses reflects the mobility of incompatible elements in the fluid phase during infiltration metasomatism.

Comparison of the concentration of elements in the lenses (Figure 22) to that in Group II metasomatite (Figure 19), indicate that the lenses have lower concentrations of Na_2O , Lu, Hf, and Th relative to Group II. K_2O , Cr, La, Ce, Sm, and Eu have much higher

concentrations in the lenses. Sc, Fe, and Co also have higher concentrations in the lenses relative to Group II metasomatite. Elements that were detected in the lenses, but not in Group II metasomatite, are Cs, Ba, Rb, and Zn.

Group II metasomatite commonly shows greater gains and losses relative to Group I. However it shows a smaller gain in La, Ce, and Cr. This data indicate that most of the elements mobile in diffusion-dominated processes in these rocks were also mobile, and commonly more concentrated in fluids, in infiltration-dominated processes. It also indicates that incompatible elements became highly concentrated within the dilatant lenses during deformation.

Figure 32 shows that the elements Zr, Zn, Lu, Hf, Al_2O_3 , La, TiO_2 , and MnO, which define the isocon line, are immobile in infiltration-dominated systems in metaultramafic rocks. Elements that were gained during metasomatism are CaO, P_2O_5 , Na_2O , K_2O , Sc, Sm, and Eu. Elements lost are SiO_2 , MgO, Cr, FeO, Co, Th, and Ce. Figure 33 shows the percent gains and losses for these elements. Figure 32 also indicates that the elements Ba, Ga, and Rb were gained and Sr, Ni, and V were lost during metasomatism.

Figure 35 summarizes the relationship of the gains and losses of elements between the mafic and ultramafic bulk compositions. Table XXIV lists the mobile and

Figure 35. Summary of the gains and losses of elements between mafic and ultramafic bulk compositions from metasomatic alteration.

TABLE XXIV

SUMMARY OF MOBILE AND IMMOBILE ELEMENTS IN
DIFFUSION- AND INFILTRATION-DOMINATED
SYSTEMS FOR EACH BULK COMPOSITIONSMETASOMATITE↔AMPHIBOLITE
(diffusion)

Immobile elements:

Nb, Zr, P_2O_5
 Zn, CaO, Ga, V
 TiO_2 , SiO_2

Mobile elements:

Na_2O , K_2O , MgO, FeO
 Al_2O_3 , MnO, Sc
 Cr, Co, Ni, Cu
 La, Ce, Sm, Eu, Lu, Hf
 Th, Rb, Sr, Ba, Y

METASOMATITE IN SHEARS↔AMPHIBOLITE
(infiltration)

Immobile elements:

K_2O , MnO, Ce
 TiO_2

Mobile elements:

SiO_2 , Al_2O_3 , Na_2O
 FeO, CaO, MgO, P_2O_5
 Sc, Cr, Co
 La, Sm, Eu, Lu, Hf, Th

METASOMATIZED METAULTRAMAFIC↔LEAST
ALTERED ULTRAMAFIC

Immobile elements:

Zr, Zn, Lu, Hf
 Al_2O_3 , La, TiO
 MnO

Mobile elements:

SiO_2 , Na_2O , K_2O
 FeO, CaO, MgO, P_2O_5
 Sc, Cr, Co, Ni, Ga
 Ce, Sm, Eu, Th, Rb, Sr
 V, Ba, Y

immobile elements for each bulk composition under diffusion- and infiltration-dominated systems for the major groups of elements. In general, 1) alkali metals tend to be mobile and move from mafic into ultramafic compositions; 2) the alkali earth metal CaO was relatively immobile, and MgO was mobile and moves into mafic from ultramafic compositions; 3) Al was mobile in the metasomatism of mafic rocks, but relatively immobile in ultramafic rocks; 4) the transition elements of Period 4 were mobile, and generally move from ultramafic into mafic bulk compositions; 5) the lanthanides and Hf were mobile, and show enrichment in both mafic and ultramafic compositions; 6) Th was mobile and is depleted in both bulk compositions, and 7) the incompatible elements Cs, Rb, and Ba were mobile and were enriched in the fluid phase along shear zones.

The metasomatism between mafic and ultramafic bulk compositions may be examined using the Gibbs phase rule, $f = c - p + 2$, and Korzhinskii's (1965) reformulation, $f = c - p + 2 - m$. The amphibolite contains the 4-phase mineral assemblage hornblende-plagioclase-quartz-apatite. The composition of the rock may be approximated in the 7-component system Al_2O_3 -CaO-FeO-MgO-SiO₂-P₂O₅-H₂O. Apatite is the only phase containing P₂O₅, and may be removed from consideration. Thus the system may be defined by 3 solid phases and 6 components. At constant

pressure and temperature conditions, the system would have a variance of 3. The components Na_2O , K_2O , and trace elements may be neglected due to their low concentration in these rocks. The hornblende metasomatite contains the 1-phase assemblage consisting of hornblende. The composition of the rock is also approximated by the 6-component system as in amphibolite. However, it has been shown that in both diffusion- and infiltration-dominated systems, the components Al_2O_3 , FeO , MgO , and SiO_2 , and H_2O are mobile. The number of phases that are possible in a metasomatic rock is given by the expression $p \leq c - m$. In these rocks, $p = 6 - 5 = 1$, indicating that these rocks should contain one solid phase. The 2-phase assemblage hornblende-apatite may be accounted for by the addition of P_2O_5 to the system. The variance of this system at constant P and T is zero.

Pre-metasomatism metaultramafic rocks contained the 3-phase mineral assemblage olivine-orthopyroxene-chromite. The composition of these rocks may be approximated by the 4-component system $\text{MgO}-\text{FeO}-\text{SiO}_2-\text{Cr}_2\text{O}_3$. The variance of this assemblage at constant P and T would be one. Upon metasomatism, the components Al_2O_3 and CaO infiltrated the ultramafic bulk composition in a fluid phase, resulting in the 1- and 2-phase mineral assemblage $\text{Mg-hornblende} \pm \text{opaque}$. The composition of $\text{Mg-hornblende-opaque}$ may be approximated in the system $\text{SiO}_2-\text{CaO}-\text{Al}_2\text{O}_3-\text{MgO}-\text{FeO}-\text{H}_2\text{O}$.

The components SiO_2 , CaO , MgO , and H_2O are shown to be mobile in the fluid phase. Thus the number of phases possible is $c-m=6-4=2$, requiring a 1- or 2-phase assemblage in the rock. The variance of this system at constant P and T would be one for a 1-phase assemblage. These results appear to be reasonably consistent with the experimental results of Vidale and Hewitt (1973). At constant P and T , their starting system had a variance of one, and their resultant metasomatic system, a variance of zero.

SUMMARY

The rocks in the Branham Lakes area of the Tobacco Root Mountains have undergone polyphase metamorphism. The results of this study have shown the following:

1. Textural and mineralogical evidence indicates that the amphibolite unit, containing amphibolite, metaultramafic rocks, and metasomatite, was tectonically juxtaposed against interlayered sequences to the north and south prior to the peak metamorphism;

2. Three groups of contemporary mineral assemblages, each forming under a different set of conditions, occur in mafic and ultramafic bulk compositions and are summarized in Figure 34;

3. The grade of metamorphism has been established on the basis of mineralogy to be of the upper amphibolite facies. The conditions of the peak metamorphism in the region, determined by Immega and Klein (1976), and Friberg (1976), was approximately 600-800° C and 4-6 kb pressure. Two post peak metamorphism events are indicated by the mineral associations;

4. The mobility of elements during metasomatism at the conditions of the peak metamorphism has been determined and summarized in Table XXIV. Consideration of

the phase rule indicates that the systems are somewhat consistent with those analyzed experimentally by Vidale and Hewitt (1973).

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APPENDIX

There are three parts to the method of study for this project: 1) field work, 2) analytical work, and 3) data reduction. Each part contains the possibility of error, and will be examined separately. Although pure objectivity is desirable in any research problem, there is generally a certain degree of subconscious subjectivity that cannot be ruled out as a source of error.

FIELD WORK

Errors in field work may be broken down into sampling, mapping, and geologic interpretation. Outcrop availability and weathering affect sampling. In the study area, amphibolite is resistant to weathering and form many fresh outcrops. In contrast, metaultramafic rocks are generally highly weathered and form few outcrops. Thus, the collection of metaultramafic rock samples were biased toward the least weathered samples.

Two kinds of geologic maps were produced in the study area: a lage scale geologic map covering about 10 km², and a small scale geologic map covering about 0.5 km². The large scale map was produced using existing USGS topographic maps. Error in the production of this map may

result from inaccurate location of geologic boundaries. Inaccuracy in placing these boundaries may result from inaccuracies inherent in the topographic maps and inaccuracy in identifying position in the field.

The small scale map was produced using a plane table and alidade. Errors may result in the inaccuracy of the instruments and the experience of the operators. Backsighting and repetition of some sights were performed to test the precision of readings. These generally agreed to within 0.1 m.

Errors resulting from geologic interpretation in the field are generally a result of the size of an area and the degree of background knowledge. In a large area that contains numerous outcrops, the number of samples that can be collected is limited by the time spent in the field. Therefore, knowledge of what samples are needed for a project is required for the most efficient use of time in collecting those samples. The knowledge of what samples are needed for a project depends on an understanding of the subject. Thus, background knowledge is essential to the correct sampling of an area and must be assumed for the project to be valid. Since field work depends on background knowledge, interpretation in the field is based on that knowledge. A different interpretation may be overlooked simply because the background knowledge used did not include the basis for a different interpretation.

ANALYTICAL WORK

The errors that occur from analytical work result from instrument accuracies and bias and contamination during samples preparation. Instruments are periodically calibrated, and are expected to give results that are of a standard acceptability. Each kind of instrument has inherent limitations, which are known. Thus, by identifying the method of analysis, some degree of error is assumed for each instrument.

Samples selected for analysis are generally samples that are least weathered, since weathering results in undesirable chemical contributions. However, most metaultramafic samples are weathered to some degree. For INAA, samples are chipped with a steel chipper. In order to cut down contamination by the steel, rock chips that show obvious impact are picked out and discarded, thus introducing another bias into sample preparation. Additional bias is reduced by sample splitting in an attempt to make the sample as homogeneous as possible.

Samples used for petrographic analysis represent only a small area of a rock. However, using thin sections in conjunction with hand samples reduces the bias of a single thin section. Amphibolite samples and metasomatite samples vary little, and a thin section can be assumed to be reasonably representative. In contrast, metaultramafic

rocks vary significantly, thus enough thin sections are produced to be reasonably representative of that variation.

Errors from contamination are most important for INAA. Possibility of contamination is reduced by cleaning the instruments used in sample preparation before each sample is prepared, cleaning the containers used to hold each sample, and cutting down the amount of handling of each sample.

DATA REDUCTION

Errors in data reduction may result primarily from errors inherited from field work and analytical work. However, a certain degree of subjectivity is expected in data reduction. As an example, if ten samples of amphibolite were analyzed geochemically, and the compositions of all but one agreed within a small standard deviation, the one that does not agree may be disregarded under the assumption that it is not a representative sample of amphibolite. It may contain within it a localized composition different from "normal" amphibolite. In a highly metamorphosed terrain, this assumption is valid since there may be small localized areas of different compositions that result from a number of possible mechanisms.

There are numerous ways that data may be used, and it

depends, again, on background knowledge. Data will be used to support and argument or interpretation. When discrepancies arise, they may be noted, or assumptions may be made that reduce their impact. As data reduction progresses, new ideas or interpretations may arise that cannot be well supported by the field and analytical work that was performed. Therefore, errors in the final analyses may result from the limitations imposed at the beginning of a project.