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**THE PETROLOGY OF THE PRECAMBRIAN ROOF PENDANTS
THOMPSON PEAK, SAWTOOTH MOUNTAINS, IDAHO**

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in partial fulfillment of the requirements for the Upper Division Honors Program
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PETROLOGY OF THE PRECAMBRIAN ROOF PENDANTS OF THOMPSON PEAK, SAWTOOTH MOUNTAINS, IDAHO

INTRODUCTION

Understanding the evolution of the Earth's crust is the focus of the study of metamorphism and metamorphic rocks. Metamorphic rocks are sedimentary, igneous and other metamorphic rocks that have been compositionally and texturally altered in the solid state by changes in pressure (P) and temperature (T) conditions of their environment. By studying the temperatures and pressures of formation of rocks and the changing conditions to which rocks are subjected in their histories, information is gained about the formation of the Earth's crust.

In order to find the temperatures and pressures of formation of a group of rocks, the mineral assemblages of the rocks must be identified. The minerals making up a metamorphic rock are the result of both the bulk composition (the original chemistry) of the original rock and the temperatures and pressures to which the rock was exposed. (e.g., Yardley, 1991; Raymond, 1995). The stability field for each mineral changes with changes in P and T. Minerals coexist in a metamorphic rock when their stability fields intersect or coincide and when the bulk composition is appropriate for the formation of the minerals. Mineral assemblages for a particular bulk composition, then, change with changing P and T. Mineral textures are also important in studying the metamorphic events encountered by a rock or group of rocks. Textures indicate changes in chemical composition of minerals, reactions with surrounding minerals, contact with fluid phases, and extent of deformation during metamorphism (e.g., Yardley, 1991; Spear, 1993). Thus, textures provide historical information about the rocks.

Since P-T conditions are indicated by present mineral assemblages and textures, the metamorphic history of a group of rocks can be described by identification of the varying mineral assemblages within the group of rocks. Plotting the course of metamorphic events that rocks have experienced, e.g. the changing P-T conditions, can lead to the determination of the tectonic settings encountered by the rocks. Temperatures and pressures provide information on the depth of formation of the rocks, the conditions of their transport to the Earth's surface and their exposure at the surface.

In the Sawtooth Mountains of south-central Idaho, Precambrian metamorphic rocks are exposed as roof pendants (Figure 1). Roof pendants is a term used to describe a suite of rocks that have been brought up from depth and exposed at a high elevation, creating a roof above the rocks below. Magmas intrude underneath the metamorphic rocks and then surround them, leaving them as a pendant of the roof at high elevation. A literature search revealed that the roof pendants in the Sawtooth Mountains have not been previously described and were mapped as undifferentiated Precambrian metamorphic rocks (e.g., Reid, 1963; Fisher et al, 1983). Thompson Peak is the site of one such exposure.

PURPOSE

The purpose of this thesis is to describe the mineral assemblages and textures of metamorphic rocks collected from Thompson Peak in the Sawtooth Mountains. Petrographic analyses are made to identify assemblages and textures, which are the basis for classification of rocks and the materials with which study of the rocks' histories begins.

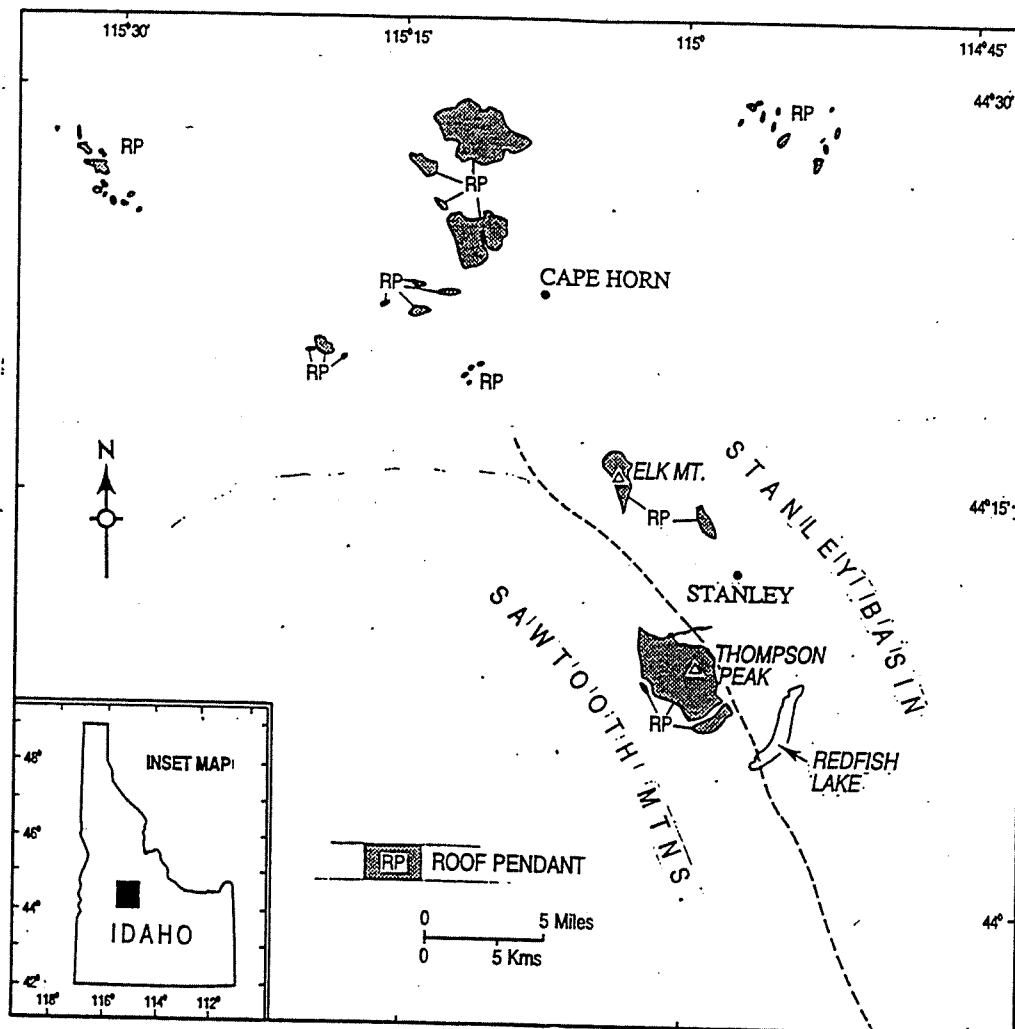


Figure 1. Location map of known PreCambrian roof pendants (RP, red) within the northwestern portion of Sawtooth Mountains, ID and to the north. The approximate outer limit of exposure of the STM is shown by the boundary faults. Long glacial moraines (ca. 4 mi) extent from the mountains into the adjacent Stanley Basin (floored by Quaternary (Qal) alluvium). Investigations focus on the Thompson Peak and Elk Mountain regions. The town of Stanley and Thompson Peak (white triangle) are shown for reference. Light pink represents rocks of the Idaho Batholith. Locations are taken from Fisher et al. (1983), modified by the PI.

The petrographic analyses of each rock are used to determine the grade of metamorphism (general P-T conditions) at which the rock was formed. Each rock is classified by this data and rocks are grouped according to those classifications. Chemical analyses are made to determine the pressure and temperature of the rock's formation. This provides information which can be used to determine the tectonic setting under which the roof pendant rocks formed. This determination will then be incorporated into continuing studies of the developmental history of the North American craton. Finding the age correlation of the Thompson Peak metamorphic rocks to those in surrounding regions will advance our understanding of the accretionary history of the North American craton during Precambrian time. Because of their antiquity and the rare exposures of Precambrian rocks in this region, the study of the Thompson Peak rocks is of paramount importance in understanding the development of the continental crust of North America during the Precambrian.

GEOLOGICAL SETTING

The Sawtooth Mountain Range lies in south-central Idaho (Figure 2). The Range is located at the northernmost extension of the Basin and Range region and the Rocky Mountains. The Sawtooth Mountains are a fault block mountain range, bounded by two large scale northwest-trending faults. The Range was uplifted about 1 Ma when extensive faulting occurred (Reed, 1963) and now rises 5000 feet over the Stanley Basin to the east. The Stanley Basin is the corresponding downthrown block to the unthrown mountain range (Reed, 1963).

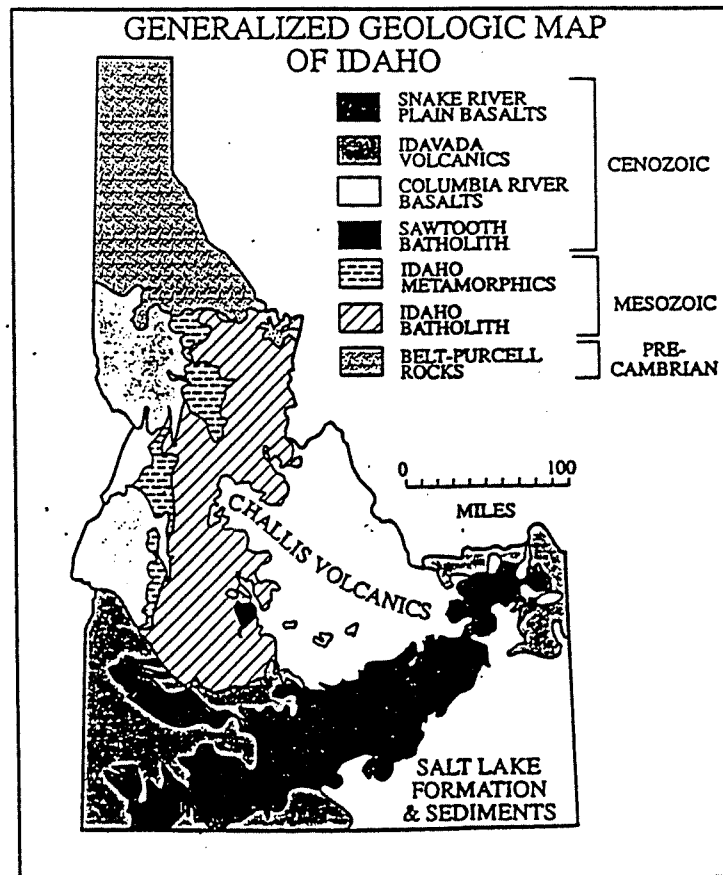


Figure 2. Generalized Geologic Map of Idaho displaying major rock units (after Bond 1978). The Sawtooth Mountains (fushia) are located in central Idaho within the Idaho Batholith. Belt series metamorphics are to the north.

A portion of the complex geological history of the Sawtooth Mountain Range begins with the intrusion of the Idaho Batholith (108 Ma, Maley, 1987) into Precambrian metamorphic rocks throughout most of Idaho during the early Late Cretaceous. The extensive Idaho Batholith covers over 20,000 square miles of Idaho. Compositionally, the Idaho Batholith varies from diorite and granodiorite to quartz monzonite (e.g., Reed, 1963). In the Tertiary, 40-45 Ma, the Sawtooth Batholith intruded the Idaho Batholith (e.g. Reed, 1963; Maley, 1987). The Sawtooth Batholith is composed primarily of granitoids rich in pink K-feldspar. The leucocratic (white/gray) quartz monzonite of the Idaho Batholith is very distinct from the pink coarser-grained granitic rocks of the Sawtooth Batholith. The Sawtooth Batholith is underlain and surrounded by the rocks of the southern portion of the Idaho Batholith. The southern portion of the Idaho Batholith was emplaced ca. 75-100 Ma (e.g. Armstrong, et al, 1977).

The high-grade metamorphic rocks of this study are part of a suite of roof pendant rocks near Thompson Peak, elevation 10,843', the highest elevation in the Sawtooth Mountains. The primary study area concentrated on rocks that surround Profile Lake (which has great trout fishing), one of the many cirque lakes in the Sawtooth Mountains. (Figure 3). The metamorphic rocks are located along the north ridge of Profile Lake and to the northwest. Metamorphic rocks to the northwest are outcropped in the saddle between Thompson Peak and Williams Peak to the north.

The Sawtooth Mountains derive their name from their steep, jagged ridges, created by Pleistocene glaciation, differential erosion and two sets of large-scale fractures that cross the Range (e.g. Norton, 1986; Reed, 1963). Glaciation also left morainal deposits

up to four miles in length with several thousand feet of vertical extent. The rugged topography makes the hike in to Thompson Peak from the east a long trek through wildflower meadows and across talus slopes and rock faces with spectacular views of Stanley Basin, Redfish Lake and the White Cloud Mountains to the east (Figure 4). Glacial debris and moraines overlie the eastern boundary fault that separates the Sawtooth Range from Stanley Basin (e.g., Armstrong, 1977).

METHODS OF INVESTIGATION

Field Methods

Backpacking and long hikes were required to enter the remote high region of Thompson Peak to collect rocks for study and analysis. Mapping of the geologic units and sampling of metamorphic rocks were performed by Prof. Barb Dutrow, Mario Giarmata (Univ. of California, Stanislaus) and Susan Anderson in the Thompson Peak region in July, 1994. Further mapping and sampling was done in August, 1995 by Profs. Dutrow and Darrell Henry. Field notes were maintained by B. Dutrow to fully document the geological observations of the roof pendants and their geographical setting. Preliminary mapping of rock types and structures was done on sheets of mylar placed over enlarged (3X) aerial photographs because topographic maps did not provide sufficient detail. Sample locations and geologic units are shown in Figure 5. Among the units mapped are grt-bio gneisses, pyx gneisses, calc-silicates, quartzites, marbles, amphibolites and sulfidic schists. Contacts between the units were noted as well contacts with felsic and mafic dikes that cross-cut a number of the units. Boudins of calc-silicates were

Figures 3 & 4 Photo of Profile Lake, Photo of White Clouds & Stanley Basin

observed in sulfidic and gneissic units. Areas of metasomatism of calc-silicates were recorded along with observations of the impact, such as hydration, of the dikes on the rocks. The exposures contained various mixed units that were mapped as mixed units with notations of the various rock types within them. The two mylonite zones were well-documented, both on the aerial photograph map and by 35 mm photographs and written documentation. Geologic units exhibiting effects of the mylonitization were also clearly identified on the preliminary map. Folding within the gneissic units and the extensive marbles was documented on the map and in the field notes. 35mm color photographs were taken of the outcrop areas and the surrounding field area. Field work yielded approximately 100 - 150 metamorphic and igneous rock samples from the Thompson Peak region.

Laboratory Methods

Thin sections were made from the collected samples and petrographic analyses were completed with an optical microscope. Rock types were determined through identification of mineral assemblages and textures. Photomicrographs were taken with the optical microscope to record the observed assemblages and rock textures which are presented in this report. Those metamorphic rocks with the correct mineral assemblages for determination of pressure (P) and temperature (T) conditions of formation were chosen for further chemical analysis and application of geothermobarometric methods. Assemblages and textures are the basis for determination of the P-T path of the roof pendants. This data was integrated to construct a preliminary P-T path for the roof pendants and is used to suggest a possible tectonic environment of formation.

Figure 5 Preliminary Geol. Map by B. Dutrow

PETROLOGY OF THE METAMORPHIC ROCKS

Petrographic analyses are descriptions and evaluations, made with the optical microscope, of rocks and their constituent minerals and are made in order to classify rocks by their mineral assemblages and textures. Petrology of the roof pendants encompasses the study of the rocks both in hand sample and thin section. Rock types identified in the Thompson Peak region are biotite-pyroxene gneisses, quartzites \pm Cr-musc \pm bio \pm pl, amphibolites, pyrobolites, calc-silicates, calcite marbles, and sillimanite-biotite-garnet gneisses. Of the samples collected, about 55 thin section were analyzed. The petrographic analyses made here were used to choose specific thin sections for chemical analysis. Mineral abbreviations are after Kretz (1983) and are listed in Table I. Chemical analyses reported were made by Darrell Henry with the electron microprobe and are stated in mole proportions (e.g., An₃₅ represents 35% An). Modal amounts of various minerals were done visually. These estimates are given in Table II. Mineral assemblages for the rocks analyzed are presented in Table III. Grain sizes were also measured. The following divisions were used in this study: coarse ($>750\ \mu$), medium ($125\text{--}750\ \mu$), and fine ($<125\ \mu$) grained ($1\ \mu = 10^{-6}\text{ m}$). Samples were classified by rock type. Characteristics of each rock group classified follow.

TABLE I: Generalized Mineral Formula
Major Rock-forming Minerals

Mineral Name	Abbr.*	Chemical Formula
Amphibole	Amp	$(\text{Ca, Na, K})_2(\text{Mg, Fe}^{2+})_5(\text{Si, Al})_8\text{O}_{22}(\text{OH})_2$
Actinolite	Act	$\text{Ca}_2(\text{Mg, Fe}^{2+})_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Cummingtonite	Cum	$(\text{Mg, Fe}^{2+})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$
Hornblende	Hbl	$(\text{Na, K})_{0-1}\text{Ca}_2(\text{Fe, Mg})_5(\text{Si, Al})_8\text{O}_{22}(\text{OH})_2$
Pargasite	Prg	$\text{NaCa}_2(\text{Fe, Mg})_4\text{Al}(\text{Si}_6\text{Al}_2)\text{O}_{22}(\text{OH})_2$
Tremolite	Tr	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Tschermakite	Ts	$\text{Ca}_2\text{Mg}_3\text{Al}_2(\text{Si}_6\text{Al}_2)\text{O}_{22}(\text{OH})_2$
Biotite	Bio	$\text{K}(\text{Fe, Mg})_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$
Clinopyroxene	Cpx	$\text{Ca}(\text{Mg, Fe})\text{Si}_2\text{O}_6$
Diopside	Cpx	$\text{CaMgSi}_2\text{O}_6$
Garnet	Grt	$(\text{Fe, Mg, Ca})_3\text{Al}_2\text{Si}_3\text{O}_{12}$
Margarite	Mrg	$\text{CaAl}_2(\text{Al}_2\text{Si}_2)\text{O}_{10}(\text{OH})_2$
Muscovite	Ms	$\text{KAl}_2(\text{AlSi}_3)\text{O}_{10}(\text{OH})_2$
Orthoclase	Ksp	KAlSi_3O_8
Orthopyroxene	Opx	$(\text{Mg, Fe})_2\text{Si}_2\text{O}_6$
Phlogopite	Phl	$\text{KMg}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$
Plagioclase	Pl	$(\text{Ca, Na})\text{Al}(\text{Si, Al})_3\text{O}_8$
Albite	Ab	$\text{NaAlSi}_3\text{O}_8$
Anorthite	An	$\text{CaAl}_2\text{Si}_2\text{O}_8$
Prehnite	Prh	$\text{Ca}_2\text{Al}(\text{AlSi}_3)\text{O}_{10}(\text{OH})_2$
Quartz	Qtz	SiO_2
Sillimanite	Sil	Al_2SiO_5

**TABLE I (cont): Generalized Mineral Formula
Accessory Minerals**

Mineral Name	Abbr.*	Chemical Formula
Allanite	Aln	$(\text{Ca}, \text{Ce})_3\text{FeAl}_2\text{Si}_3\text{O}_{12}(\text{OH})$
Apatite	Ap	$\text{Ca}_5(\text{PO}_4)_3$
Calcite	Cal	CaCO_3
Chlorite	Chl	$(\text{Fe}, \text{Mg})_5\text{Al}_3\text{Si}_3\text{O}_{10}(\text{OH})_8$
Clinzoisite	Czo	$\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH})$
Epidote	Ep	$\text{Ca}_2(\text{Al}, \text{Fe})_3\text{Si}_3\text{O}_{12}(\text{OH})$
Graphite	Gr	C
Hematite	Hem	Fe_2O_3
Ilmenite	Ilm	FeTiO_3
Magnetite	Mag	Fe_3O_4
Pyrite	Py	FeS
Pyrrhotite	Po	Fe_{1-x}S
Rutile	Rt	TiO_2
Titanite	Ttn	CaTiSiO_5
Zircon	Zrn	ZrSiO_4

*after Kretz, 1983.

[illegible]

Aluminous and mafic gneisses

Rocks that show alternating bands of light and dark minerals are considered to have a gneissic texture. This texture is created by the segregation of compositionally similar minerals (e.g., quartz and feldspars in light bands; micas, amphiboles and pyroxenes in dark bands) as a result of deformation. Minerals with elongate or prismatic habits align themselves parallel to one another in a planar fabric. Those Thompson Peak metamorphic rocks in which the gneissic textures are well-developed are classified as gneisses. Further classification of the gneisses is made based on rock composition. Compositionally gneissic rocks in the roof pendants range from very aluminous compositions characterized by garnet and aluminosilicate, to more mafic compositions characterized by mafic minerals such as amphibole and pyroxene. Descriptions of hand samples and thin sections are given.

Megascopic Descriptions: Aluminous and Mafic Gneisses

Most hand specimens of the aluminous and mafic gneisses are undeformed but a few of these gneissic rocks do exhibit some isoclinal folding. Lineations are distinctive. Garnets are easily identifiable by their red-pink color and rounded-hexagonal habit in cross-section. Blades of sillimanite are also distinguishable in hand samples of the aluminous gneisses. The high modal amounts of mafic minerals in the gneissic rocks gives them an overall dark color. Grains in these medium to coarse-grained gneisses are not equidimensional.

Petrographic Descriptions: Aluminous and Mafic Gneisses

Review of thin sections of the aluminous and mafic gneisses show that, generally, they contain both coarse-grained quartz and recrystallized quartz with total quartz modal amounts as great as 25% in quartz-rich samples. Plagioclase, present from 15% to 20%, is partially to nearly completely altered to sericite, is poikiloblastic and shows some exsolution. Pericline twinning and albite twinning are common in all of the gneissic rocks. Quartz and feldspar veins characteristically show growth of anomalously gray-brown birefringent chlorite along the insides of the vein walls. Minor amounts of K-feldspar (<5%), usually with fairly well-developed grid-twinning, is found in most of the gneissic rocks, but is lacking in others. A few gneisses actually show extreme alteration or overprinting by both fine- and medium-grained muscovite, making it abundant (up to 50-60%) in those samples.

Petrographic Descriptions: Aluminous Gneisses

Aluminous gneisses contain $\text{bio} + \text{pl}(\text{An}_{35}) + \text{grt} + \text{qtz} + \text{ilm} \pm \text{sil} \pm \text{ksp} + \text{zr} \pm \text{chl}$ (Tables I, II, & III). Garnets are present in varying quantities. Most of these gneisses contain very large garnet grains, making modal amounts difficult to determine. In most cases, a few grains account for significant modal amounts (20%). Plagioclase halos are found around garnets in one sil-bio-grt gneiss sample, suggesting a reaction relationship (Figure 6). Garnet porphyroblasts are poikiloblastic and many times highly fractured. Replacement by green chlorite and red-brown biotite along edges and fractures is common. Biotite is present up to 25% in these aluminous gneissic rocks. It typically has deep red-orange to brown pleochroism. However, some exhibit light orange to colorless

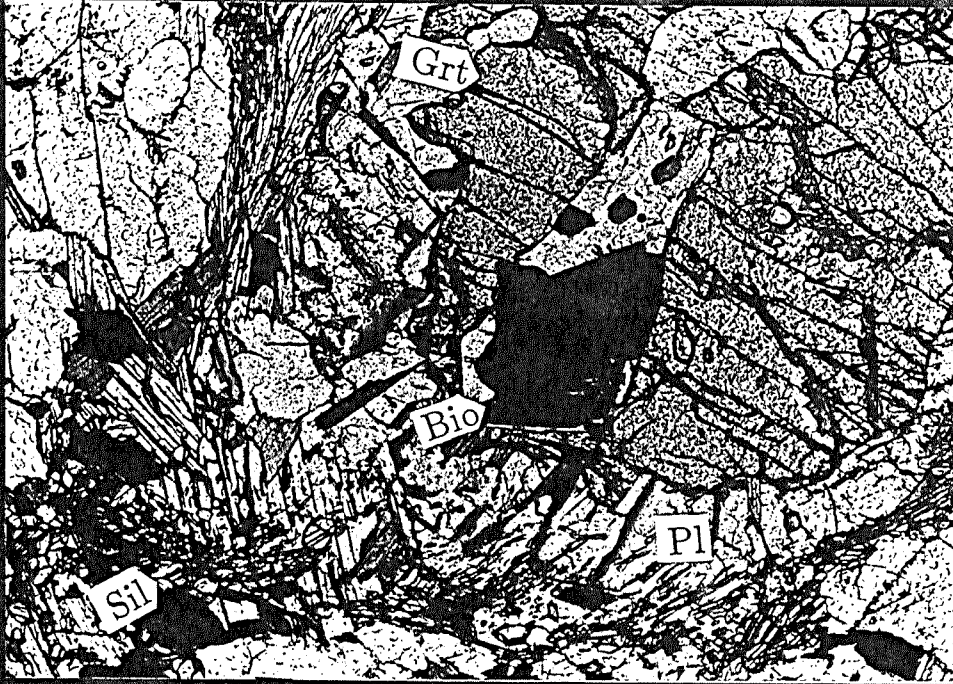


Figure 6: ST-95-08 Folded sillimanite-biotite gneiss. Embayed grt; pl halo around grt; sil, bio, ms surrounding grt. (Plane light. FOV=5.2mm)

Figures 6 & 7

Photo ST-95-08 grt w/plag halo

Photo ST-95-08 texture w/ms, sil, bio, pl

pleochroism more typical of phlogopite (Mg-rich). The deeper red colors indicate Ti enrichment.

Fine to medium-grained colorless prismatic sillimanite is observed within layers of biotite and opaque minerals (ilmenite?) (Figures 6, 7). These high relief grains show diagonal cleavage traces typical of sillimanite. Fibrolitic sillimanite is also present, particularly within the periphery of garnet porphyroblasts. Sillimanite is present in modal amounts of up to 20%.

No amphibole is found in the equilibrium mineral assemblage in these rocks, however, clinoamphibole overprinting is prominent. Hornblendes exhibit brown centers and green rims due to compositional zoning. Cumingtonite grains in Al-gneisses exhibit characteristic albite twinning and compositional zoning with colorless centers and green rims (Figures 8a, 8b).

One bio-grt gneiss contains no aluminosilicate (such as sillimanite) but contains large muscovite-margarite-zoisite pseudomorphs (Figures 9a, 9b). The overall elongate or prismatic morphology of these pseudomorphs and the presence of kyanite in some schists indicate that muscovite, margarite and zoisite are pseudomorphs after kyanite. The pseudomorphs also contain the Fe-Ti oxides, rutile and ilmenite. The reactions controlling the growth of these pseudomorphs is $\text{ttn} + \text{mrg} + \text{an} = \text{rt} + \text{zo}$ and $\text{ttn} + \alpha\text{-qtz} + \text{mrg} = \text{rt} + \text{zo} + \text{w}$ (D. Henry & B. Dutrow, pers. comm.). This sample also contains less biotite (< 3%) than the other aluminous gneisses.

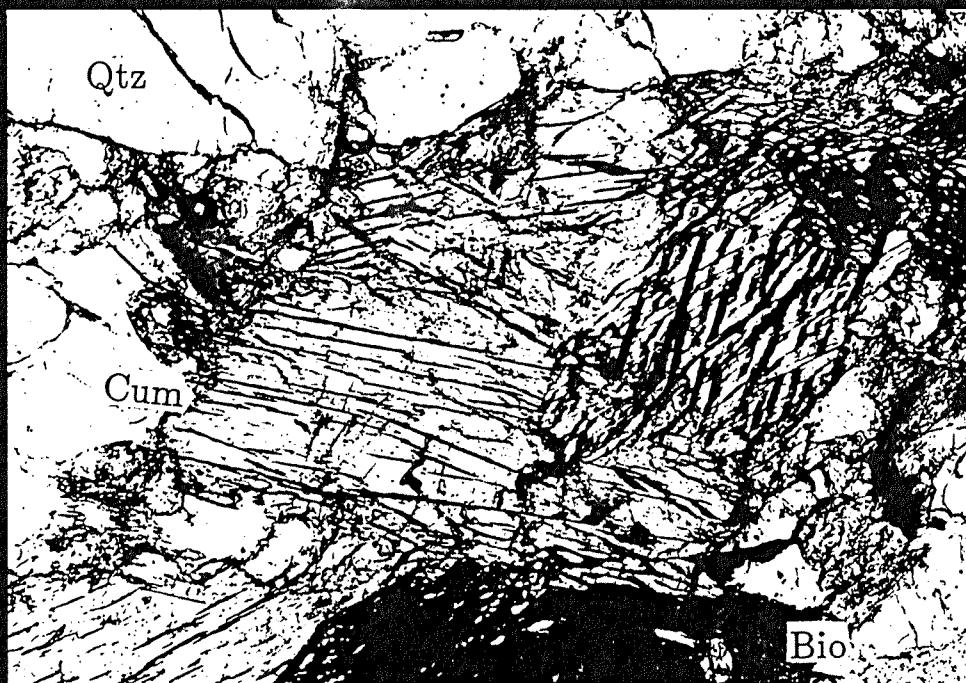


Figure 8: ST-95-07 Garnet-biotite gneiss. Overprinting of zoned cum with qtz, bio, pl represents retrograde conditions in the P-T path. (a) plane light (b) crossed nicols. FOV=5.2mm)



Figure 9: ST-95-02 Garnet-mica gneiss. Ms-mrg-zo pseudomorph. Small bladed grains are mrg and larger grains are ms. Clz also present around pseudomorphs. Represents retrograde conditions in the P-T path. ((a) plane light (b) crossed nicols. FOV=5.2mm)

Accessory minerals include chlorite and opaques. Green to yellow chlorite and opaque minerals replace biotite in trace amounts. Green colors in chlorite are related to Fe^{3+} enrichment. Fe-Ti oxides are also present in trace amounts in these aluminous gneisses.

Petrographic Descriptions: Mafic gneisses

Rocks identified as mafic gneisses have compositional banding characteristic of a gneissic texture but are more mafic in composition. Mafic gneisses contain cpx + hbl + ksp + pl (An_{52-79}) + bio + qtz + zr + apa \pm grt (Tables I, II & III). Clinopyroxene is characteristically colorless to barely green diopside and is present in modes $\leq 20\%$. Medium to coarse-grained diopside is present in masses of subhedral grains. Deformation lamellae appear in some grains. Many are fractured and broken. Amphibole is found in these mafic gneisses as a later overprinting of the diopside ($< 5\%$) (Figures 8a, 8b). Amphibole is not interpreted to represent a peak metamorphic mineral. Brown basal sections of hornblende and colorless to light green laths of cummingtonite are present in mafic gneisses in varying modal amounts. Subhedral light brown to colorless clinozoisite replaces plagioclase in some samples while colorless chlorite with anomalous gray-tan birefringence (indicating Mg-rich chlorite) replaces orange biotite.

Amphibolites

Mafic rocks identified here as amphibolites are distinct from mafic and aluminous gneisses in the abundance of amphibole, particularly hornblende, in the equilibrium mineral assemblage.

Megascopic Description

The Thompson Peak amphibolites are medium to coarse-grained. Some of the amphibolites exhibit a gneissic texture while others of the amphibolites exhibit no preferred orientation of minerals and no compositional banding and therefore have a granoblastic texture. Amphibolites are dark rocks, as mafic minerals are dominant. Some felsic bands in the gneissic samples contain small augens or “eyes” (Yardley, 1991) of quartz or feldspar. Felsic components are typically found in greater modal amounts in banded amphibolites. Granoblastic amphibolites contain green rounded knobs of amphiboles and/or pyroxenes. The amphibolites weather on the surface to brown and orange. Shiny sheet silicates are easy to identify.

Petrographic Description

The amphibolite mineral assemblage is hbl + pl ($An_{80}-An_{94}$) + cpx + bio + ttn + ilm + chl + apa + zr \pm qtz (Tables I, II & III). Amphibole is present in modal amounts of 30-60%. Equant hornblendes in equilibrium with plagioclase and clinopyroxene exhibit tan to brown and green pleochroism. Compositional resetting results in hornblende grains with brown centers and green rims. A few amphibolite samples contain hornblende that trends toward blue rims (Figure 10).

Diopside in these amphibolites is typically colorless to very light green, usually compositionally zoned with colorless centers and green rims. Many cpx grains are twinned and a substantial amount of replacement by amphibole exists, making diopside present in fairly low modal amounts (10-20%).



Figure 10: ST-95-05 Garnet-hornblende gneiss. Zoned hbl with pl inclusions; note blue rims of hbl near grt edges. (Plane light. FOV=5.2mm)

Overprints of cummingtonite and actinolite persist throughout the amphibolites.. Cummingtonite crystals show characteristic lamellar twinning and are often zoned with colorless centers and green rims. Cummingtonite is distinguished from actinolite by its lamellar twinning. Actinolite grows in large lath-like colorless grains that show no pleochroism. In a few amphibolite samples, clinoamphiboles are bright blue-green and beige pleochroic alkali amphiboles. They exhibit compositional zoning from light blue centers to dark blue rims.

Modal amounts of plagioclase in the amphibolites range from 15% to 30%. Equilibrium textures are apparent with 120° junctions among grains. Albite twinning is common but not always present. Plagioclase grains are almost always sericitized to some degree and occasionally are completely sericitized. Minor clinozoisite replacement of plagioclase exists.

K-feldspar is found in late mineralized cross-cutting veins in some amphibolites and as inclusions in hornblende. Local replacement of plagioclase by K-feldspar occurs in some grains along the rims (D. Henry, pers. comm.). K-feldspar is found in trace amounts up to 5%. In some amphibolites it is totally lacking.

Biotite in the amphibolites ranges in modal amounts from 5% to 10% and contains the orange to deep red-brown pleochroism of the biotite in the biotite-garnet gneisses. Lighter-colored grains are possibly the Mg endmember phlogopite. Occasionally, compositional zoning is seen in the birefringence of biotite grains. Colorless to light green chlorite replaces biotite and phlogopite, but is also seen in replacement of amphibole and

pyroxene to varying degrees. In the gneissic amphibolites, biotite grains exhibit preferred orientation parallel to the banding .

Quartz content ranges from trace to 30% modal amounts. In the banded amphibolites, quartz exhibits a stretched and strained anhedral grain shape, while in the granoblastic rocks quartz is euhedral to subhedral.

Large garnet grains are found in many amphibolites in modal amounts up to 10%. These are often poikiloblastic, with inclusions of plagioclase, biotite, quartz and K-feldspar. Most garnets show evidence of fracture. These fractures are filled with biotite, chlorite, and ilmenite (or ilm after bio?) along edges and fractures. In banded amphibolites, garnets take on an anastomosing texture (Figures 11a, 11b). They are intertwinning in dark bands with masses of hornblende and euhedral medium-grained plagioclase.

Ilmenite and titanite are present in most samples. Light brown titanite is observed to rim irregularly-shaped ilmenite in selected samples (Figure 12). This rimming relationship is easy to observe because they are non-opaque surrounding an opaque mineral. Brown zoned euhedral titanite crystals exhibit rainbow-like birefringence, concentric rings of high interference colors. Modal amounts are low, trace amounts to 1%. Ilmenite is generally found in association with biotite but is also seen along interfaces between plagioclase and amphibole and as isolated grains.

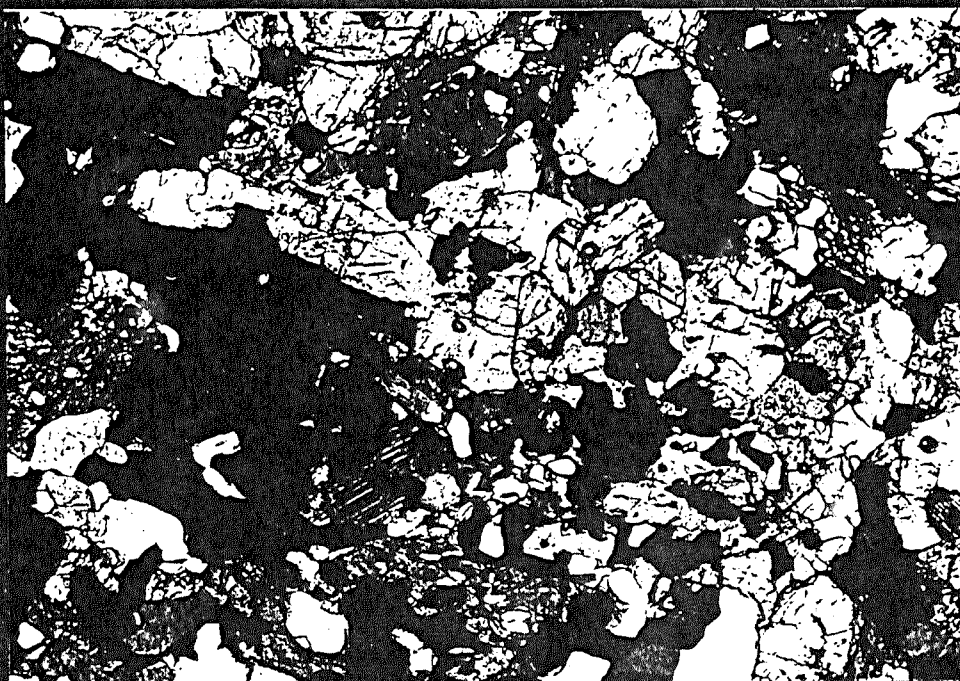
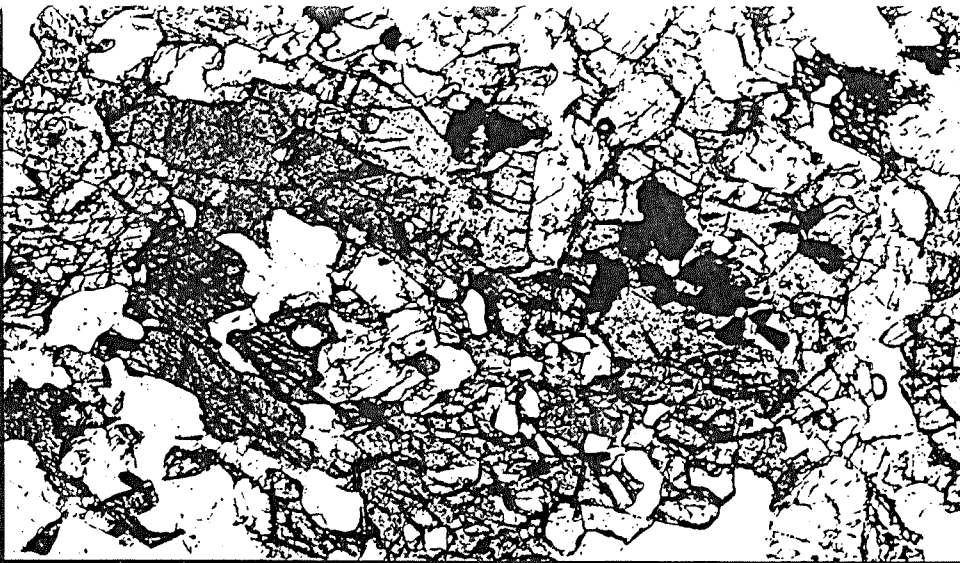


Figure 11: ST-95-06 Garnet-hornblende gneiss.
Hbl, grt, ilm, pl, qtz. ((a) plane light (b) crossed nicols.
FOV=5.2mm)

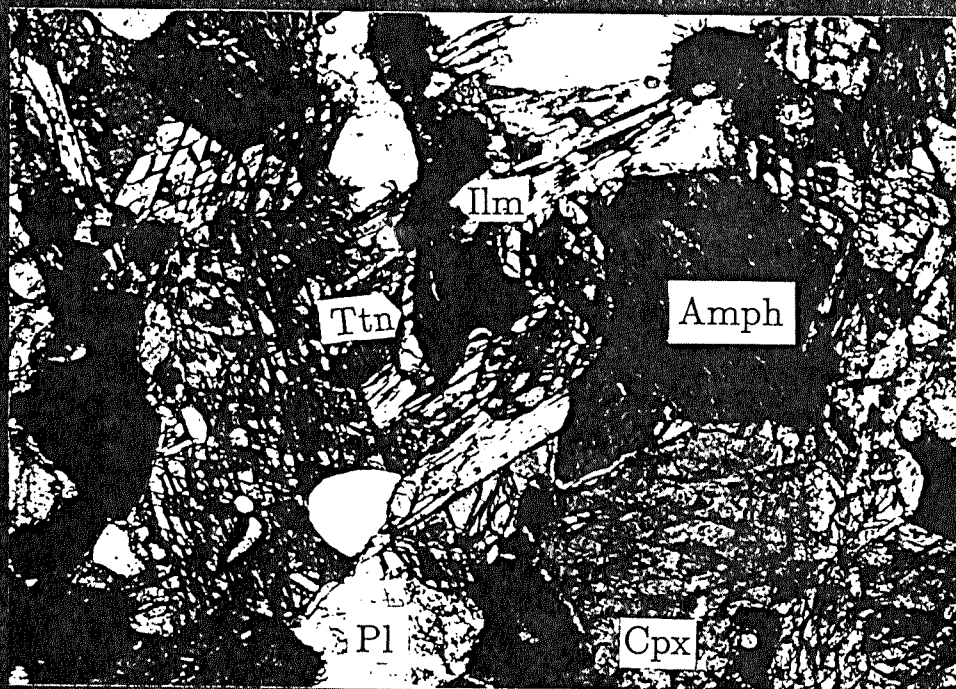


Figure 12: TP-94-06 Amphibolite. Amp, pl, ilm, ttn, cpx, bio present. Note ttn after ilm in upper center which represents retrograde conditions in the P-T path. (Crossed nicols. FOV=5.2mm)

Additional minerals include allanite, clinozoisite and apatite. Trace amounts of medium-grained yellow and brown pleochroic allanite (the Fe^{2+} endmember of the epidote group) are associated with biotite, while anomalous blue birefringent clinozoisite after plagioclase is common. Medium-grained euhedral colorless apatite grains and small, highly birefringent zircons are dispersed in trace amounts throughout these rocks.

Calc-silicates

Rocks containing abundant calcic silicate minerals and some carbonate minerals are generally referred to herein as calc-silicates. The characteristic mineral assemblage is di + czo + amp + pl + qtz + ksp + ttn + late CO_3 (Tables I, II & III). These calc-silicates have varying textures although they have very similar mineral assemblages. They range from being granoblastic, with equant euhedral to subhedral grains and no distinct preferred orientation, to having slight alignment of prismatic and elongate minerals, to exhibiting very distinctive segregation banding and alignment of mineral grains. In hand sample they are white, green and grayish-green, sometimes with a sugary texture. Clinoamphiboles in these hand samples are distinguishable by their prismatic and bladed habit and occasionally are found in radiating sprays. Mineralized veins are also observed in a few calc-silicate samples. Mylonitization has effected some of the calc-silicates. These mylonites are very fine-grained, exhibit cataclasis of grains and distinctive banding. The calc-silicates are discussed here in terms of mylonitic calc-silicates and non-mylonitic calc-silicates.

Non-mylonitic calc-silicates

The calc-silicate rocks that have not experienced mylonitic effects are mostly granoblastic with no preferred orientation of mineral grains (Figures 13a,b, 14a,b). These calc-silicates are medium to coarse-grained. Dominant minerals of the above assemblage are diopside, plagioclase and quartz. In hand specimen, diopside grains are easy to identify by their prismatic habit, 90° cleavage and green color.

Petrographic Description

Diopside in these calc-silicates is euhedral, colorless, and compositionally zoned (as seen in BSE and by the birefringence). Many grains have lamellar twinning and most exhibit, to some degree, a sieved texture, with plagioclase, K-feldspar and quartz inclusions (Figures 13a, 13b). Modal amounts range from 20% to 60%. Many diopside grains are larger than the microscopic field of view (~5.2 mm at 4X).

Plagioclase in these rocks exists in modal mounts of 5% to 20%. Most grains are sericitized and some are completely altered. Deformation lamellae and albite twinning are common. Exsolution is seen in a few samples in feldspars as a result of slow cooling of the rocks. When slow cooling occurs in Ca-plagioclase or K-feldspar, Na-plagioclase tends to exsolve within the Ca-plagioclase or K-feldspar in irregular grains. Irregular shapes of the exsolved feldspar and varying extinction angles between the two feldspars are distinguishing features of exsolution. Oscillatory extinction patterns in plagioclase under crossed polars indicates compositional zoning. Grid-twinning in K-feldspar is nearly always well-developed unlike the minor perthitic textures of microcline noted in these

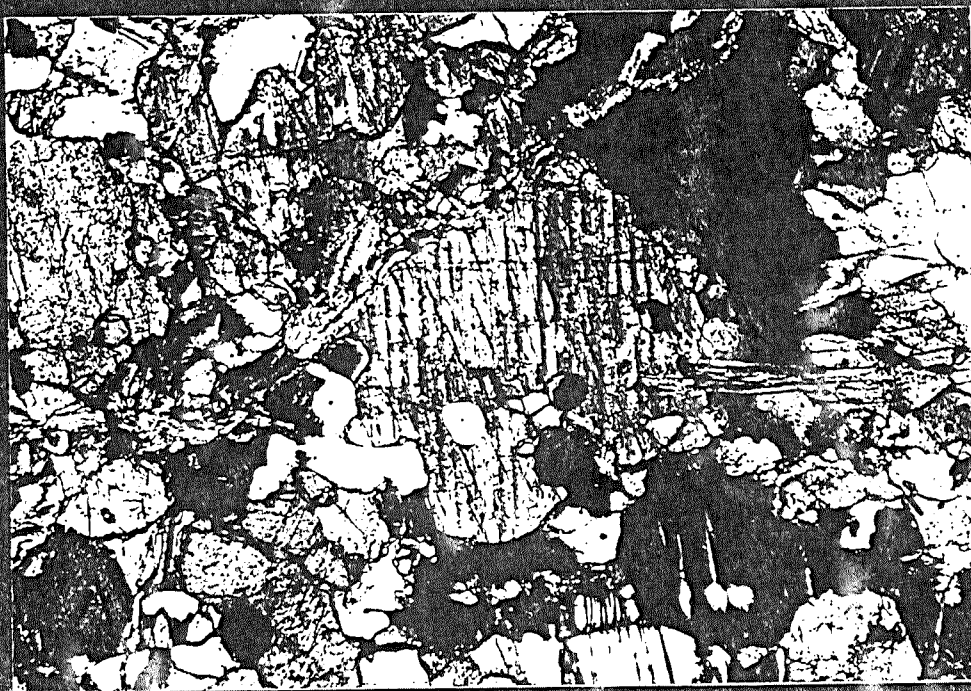
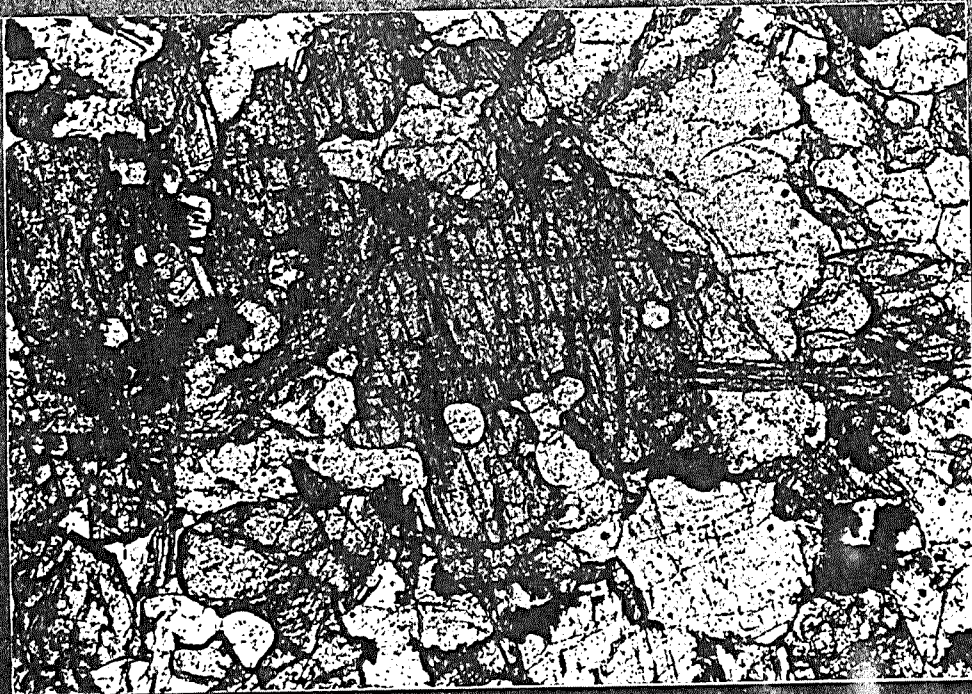


Figure 13: TP-94-23 Calc-silicate. Cpx, ksp, pl, qtz, hbl, zoned ttn. ((a) plane light (b) crossed nicols. FOV=5.2mm)



Figure 14: TP-94-36 Calc-silicate. Amp, ksp, cpx, pl, ttn, qtz. Large post-kinematic tremolite grains. ((a) plane light (b) crossed nicols. FOV=5.2mm)

rocks. A few granoblastic samples contain myrmekitic textures with K-feldspar and quartz. K-feldspar modal amounts range from trace to 30%.

Amphibole is present in small quantities, 5% to 10%, and is scarce or absent in a few samples. Colorless blades or laths of clinoamphibole, presumably tremolite, overprint clinopyroxene in all but two or three rocks (Figures 14a, 14b). These laths range in grain size from much smaller than the diopside grains to slightly longer than the width of diopside grains.

Quartz is also present to varying degrees, from nearly trace amounts of recrystallized grains along grain boundaries up to 20% of medium to coarse-grained matrix quartz. Medium to coarse-grained as well as recrystallized quartz are found in all granoblastic samples. Banded samples contain greater amounts of recrystallized quartz.

Colorless, coarse-grained anhedral to subhedral clinozoisite substantially replaces plagioclase and is also found in small amounts in the matrix. Modal amounts of clinozoisite are less than 5% on average but more calcic calc-silicates contain up to 10% yellow and blue-birefringent epidote minerals such as clinozoisite and zoisite.

Late stage carbonates, possibly calcite, are present in the non-mylonitic calc-silicates up to 10%. Most carbonate is fine-grained and massive, growing along grain boundaries. However, some rocks contain considerably larger calcite rhombs exhibiting the characteristic beige birefringence with specks of high interference colors along rims. These usually show well-developed rhombohedral cleavage and characteristic changing relief or “twinkling” (MacKenzie et al, 1980).

Accessory minerals in the non-mylonitic calc-silicates include titanite, opaques, zircon, apatite, phlogopite and chlorite. Oval and wedge-shaped titanite grains occur in trace amounts up to 5%. Small amounts of these grains have very strong orange to brown pleochroism. Opaque minerals, Fe-Ti oxides and sulfides, include elongate irregular grains of ilmenite but are present only in trace quantities. Equant zircons are ubiquitous in trace amounts throughout the calc-silicates. Apatite, however, exists in trace amounts of very small euhedral grains to aggregates of medium-grained crystals (up to 5-7%) along interfaces between zoned plagioclase grains. Peach-colored phlogopite and colorless to yellow chlorite are present in trace amounts in only two or three of these calc-silicate rocks.

Mylonitic calc-silicates: Petrographic Description

Mylonitization affects some of the Thompson Peak calc-silicates, as well as other units located near the mylonite zones. These affects are gradational in that the calc-silicates exhibit a range of cataclasts and minor to fairly extensive mylonitic textures. Segregation banding is minor in some of these rocks and very prominent in calcite-rich rocks. Mineral assemblages in the least mylonitized of these are very similar to those of the granoblastic calc-silicates described above. These partially mylonitic calc-silicates, however, show less extreme banded textures, are much finer-grained ($\sim 25\text{-}75\ \mu$) than those non-mylonitic calc-silicates and contain only minor amounts of calcite and clinozoisite.



Figure 15: ST-95-17 Mylonitic calc-silicate. Strained qtz and cpx in a matrix of qtz and cal. Fe-Ti oxides and pl present. Note brittle deformation of cpx and ductile deformation of qtz. (Crossed nicols. FOV=5.2mm)

Increasing effects of mylonitization cause some calc-silicates to be fine-grained with distinct segregation of quartz and calcite in compositional banding (Figure 15). Porphyroblasts make up about 10% to 20% of the rock. The porphyroblasts contain about 50% colorless diopside, 25% quartz and 25% plagioclase. Colorless diopside grains show evidence of brittle deformation in that they are broken and bent. Deformation lamellae appear to be pre-kinematic and are broken and bent with the diopside grains. Most of the matrix quartz is fine-grained but bands of coarser-grained quartz are found. These large grains of quartz exhibit intensive undulatory extinction. They are flattened and sheared and some appear stretched. Plagioclase porphyroblasts show little deformation but occasionally are fractured. Some sericitization was noted of plagioclase is observed.

Accessory minerals in the mylonitic calc-silicates are very similar to those found in the non-mylonitic calc-silicates. Yellowish chlorite with blue-brown-gray anomalous birefringence is found in trace amounts. Small euhedral zircons are found throughout. Opaque minerals are present in < 5% modal amounts, disseminated along grain boundaries. Clinozoisite or zoisite replaces plagioclase in < 3% modal amounts. Zoned titanite, again with concentric rings of rainbow-like birefringence, are found in association with plagioclase (<1%). K-feldspar is identifiable in the coarser-grained of these calc-silicates to < 5% modal amounts.

PRELIMINARY P-T PATH OF THE THOMPSON PEAK ROOF PENDANTS

Diagnostic mineral assemblages found in the Thompson Peak aluminous and mafic gneisses, amphibolites and calc-silicates provide information crucial to the determination of the metamorphic history of the roof pendants. The rocks' history is represented by the P-T path, which is necessary for determining the tectonic environment in which the rocks formed. The P-T path progresses through metamorphic facies that represent the grade of metamorphism, or the extent of metamorphism. Facies are defined by stable mineral assemblages, which are (in part) P and T dependent. The prograde path proceeds as the P and T of the rocks' environment increase, with burial and heating, until the peak metamorphic conditions are met. These conditions are the highest P and T the rocks encounter. The mineral assemblage stable at these peak conditions is the peak metamorphic assemblage (e.g., Yardley, 1991; Spear, 1993). This assemblage is diagnostic in that it indicates the grade of metamorphism at which peak conditions were met. A retrograde path for the rocks begins when the P-T conditions begin to decrease, such as with uplift of the rocks and infiltration of fluids. A retrogressive path will occur only there is sufficient perturbation of the conditions to change the peak temperature (e.g., Spear, 1993).

P-T conditions for seven samples of the three rock types were calculated by D. Henry (pers. comm.) using Berman's multi-equilibria approach (1991; TWQ program), which utilizes a garnet-biotite exchange geothermometer, among other techniques. An amphibole-plagioclase geothermometer (Holland et al, 1994) was also applied to determine temperatures of formation. While these methods are not discussed here, the

results of the calculations are incorporated with the petrographic analyses to formulate a preliminary P-T path for the Thompson Peak roof pendants. (This path was discussed and determined by all members of the research team, B. Dutrow, D. Henry and S. Anderson.) Schematic AFM, CFM and other ternary compositional diagrams have been constructed for the representative mineral assemblages based on limited chemical data (Figures 16-20). Phase relations are depicted in the compositional diagrams. Tielines between phases represent potential equilibria compositions of coexisting minerals. The petrogenetic grid (Figure 21) shows the preliminary P-T path determined through petrographic analyses, initial chemical analyses and geothermobarometric applications. Ternary diagrams are superimposed on the petrogenetic grid to visually represent the changing mineral assemblages along the P-T path. Photomicrographs also help visually represent this history (Figures 8a,b, 9a,b, 10, 12, 14a,b, 22).

Prograde Path

The prograde path is always the most difficult portion of the P-T path to identify because little trace of the prograde minerals are left. One part of the prograde path of the Thompson Peak roof pendants is known. Sulfidic schists, which were not analyzed in this study, contain kyanite identifiable in hand specimen. This indicates that the roof pendants, at some time in their prograde history, moved through the stability field of kyanite.

Peak Metamorphism

Peak metamorphic conditions are represented by the highest P and T the rocks have encountered. At these conditions, the peak mineral assemblage is stable and preserved in the rocks. This mineralogy is usually the dominant mineralogy of the rocks

(e.g., Spear, 1993). The conditions of peak metamorphism for the Thompson Peak roof pendants are known from the peak metamorphic assemblage and the geothermobarometry calculations. The aluminous gneisses best preserve the peak metamorphic assemblage of $\text{bio} + \text{grt} + \text{pl} (\text{An}_{35}) + \text{qtz} + \text{ilm} \pm \text{sil} \pm \text{ksp} + \text{zr} \pm \text{chl}$ (Tables I, II & III; Figure 16). In pelitic rocks such as these, sillimanite and garnet are diagnostic minerals. The relationships among garnet, biotite and sillimanite are shown in the AFM diagram in Figure 16. This assemblage suggests high grades of metamorphism.

Garnet and biotite in the aluminous and mafic gneisses were chemically analyzed with the electron microprobe (by D. Henry). Application of the Berman equilibria to the chemical and petrographic analyses (D. Henry, pers. comm.) resulted in average temperatures of 680°-795°C and average pressures of 5.0 - 7.2 kbar. These results show that equilibration of these minerals occurred within the sillimanite stability field, above the muscovite breakdown curve (Figure 21). This suggests metamorphism at upper amphibolite to granulite facies conditions. "True" granulite facies metamorphism requires the presence of orthopyroxene (e.g. Yardley, 1991; Willimas et al, 1982). The lack of orthopyroxene at intermediate pressures indicates the Al content in the bulk composition. Orthopyroxene does not contain Al in its structure. There is no formation of orthopyroxene in the pelitic rocks because the Al content in the bulk compositions of the original rocks were too high. The lack of orthopyroxene, however, does not mean that these rocks did not reach true granulite facies metamorphism. What it does mean is that the original pelitic rocks did not have the appropriate bulk compositions for the formation of clinopyroxene. The P-T calculations, the appearance of sillimanite and lack of

Aluminous Gneisses

KFMASH system: $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-MgO-FeO-K}_2\text{O-H}_2\text{O}$

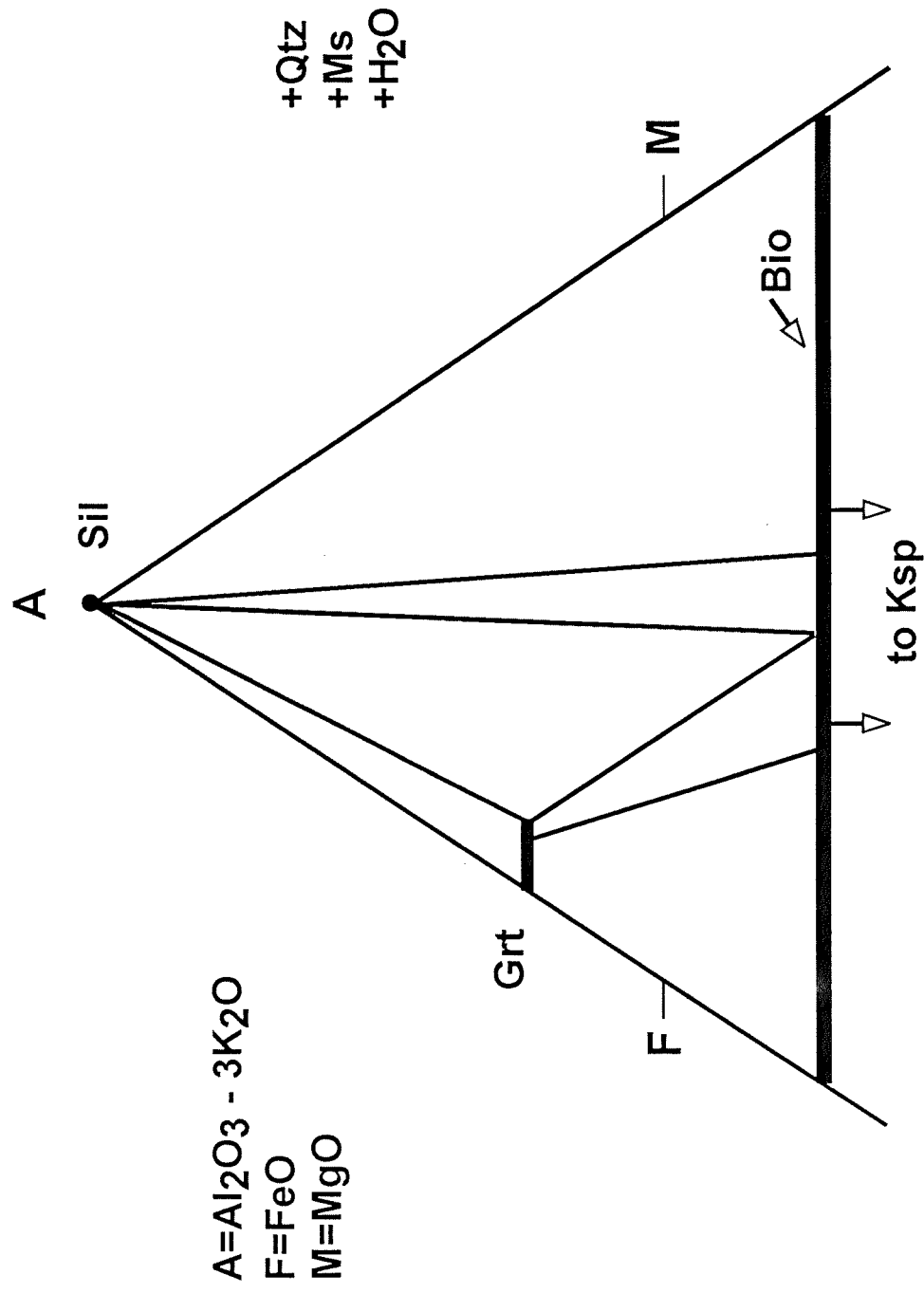


Figure 16: after Spear, 1993.

muscovite in the peak assemblage are strong evidence for upper amphibolite to granulite facies metamorphism.

Mafic gneisses contain the diagnostic mineral assemblage of cpx + hbl + ksp + pl (An₅₂₋₇₉) + bio + qtz + zr + apa ± grt (Tables I, II & III; Figure 17). Figure 17 is a CFM diagram showing the stable mineral assemblage and the relationships among minerals. The disappearance of sillimanite and appearance of amphibole and clinopyroxene reflect upper amphibolite facies metamorphism. Peak conditions for the mafic gneisses are slightly lower than that for Al-gneisses. Microprobe data and P-T calculations are not available for these rocks at this time.

Amphibolites contain the diagnostic mineral assemblage of hbl + pl(An₈₀-An₉₄) + cpx + bio + ttn + ilm + chl + apa + zr ± qtz (Tables I, II & III; Figures 17, 18). High modal amounts of amphibole, particularly hornblende, give these amphibolites their name. Figure 18 is an ACF diagram and Figure 17 is a CFM diagram showing the potential tielines between coexisting minerals. Amphibolite P-T calculations based on garnet-biotite exchange thermometry (Berman's TWQ program applied by D. Henry; pers. comm.) gives average temperatures of 610°-695° C at pressures of 5.2 - 6.3 kbars. Amphibole-plagioclase thermometry (Holland et al, 1994, applied by D. Henry; pers. comm.) resulted in temperatures of 655° -730° C at an assumed pressure of 7 kbar. These peak conditions are lower than those of the gneisses, yet are still high-grade metamorphism of the amphibolite facies (Figure 21).

The diagnostic mineral assemblage present in the calc-silicates is dio + czo + amp + pl + ksp + ttn + late CO₃ (Tables I, II & III; Figure 19). Figure 19 is a compositional

Mafic Gneisses and Amphibolites

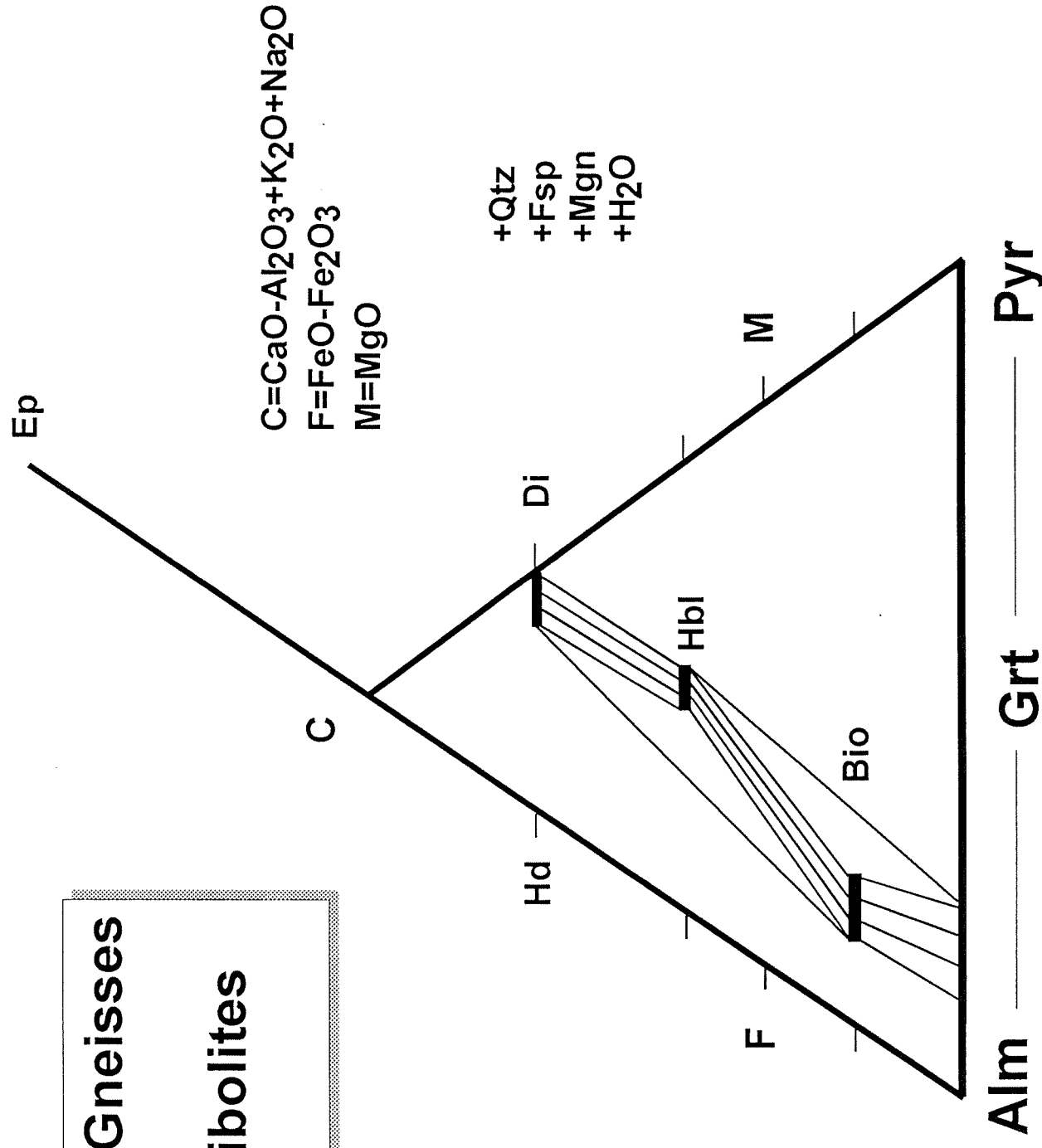


Figure 17: after Raymond, 1995, modified from Abbott, 1982)

Amphibolites

System: $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-MgO-FeO-CaO-Na}_2\text{O-H}_2\text{O}$

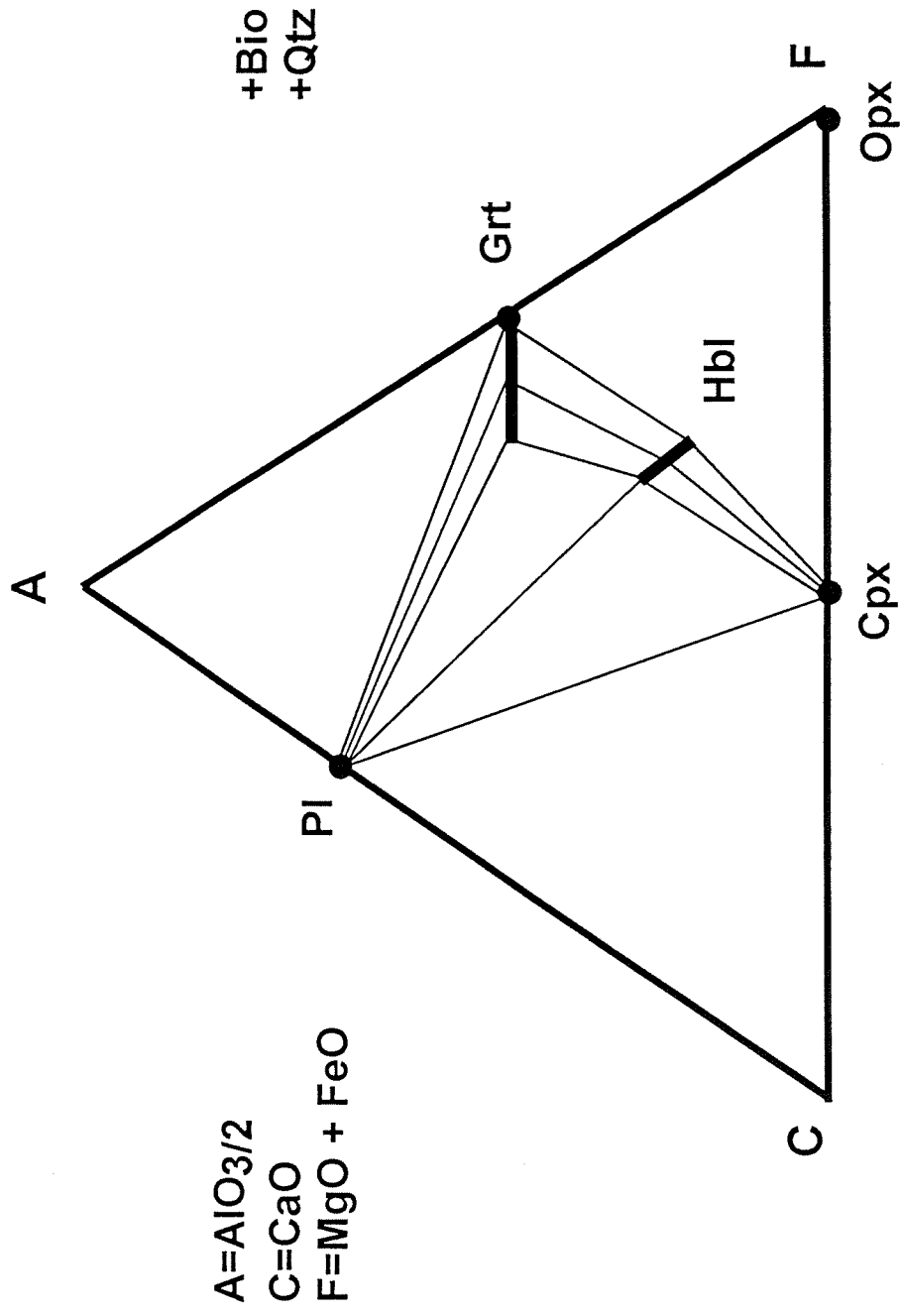


Figure 18: after Spear, 1993 and Bucher and Frey, 1994

diagram showing the dominant minerals and the relationships among them. Fewer P-T data are available for the calc-silicates but preliminary calculations based on amphibole-plagioclase equilibrium (Holland et al, 1994, by D. Henry; pers. comm.) yield average temperatures of formation of 475°-655° C at an assumed pressure of 7 kbars. These results suggest that the Thompson Peak calc-silicates formed under conditions of moderately high grades of metamorphism such as found in the lower amphibolite facies (Figure 21).

These data suggest that the Thompson Peak roof pendants met peak metamorphic conditions at temperatures and pressures of the amphibolite to granulite facies.

Retrograde Path

The retrograde portion of the P-T path begins when the peak P and T of the rocks' environment are perturbed, resulting in a decrease in P and T. The lowering of P and T occurs upon uplift and cooling of the rocks. Infiltration by fluids is important to cooling the rocks and influences the stable mineral assemblages. The retrogressive path of the roof pendants is marked by numerous overprinting features that can only occur by hydration of the rocks. Overprinting is the late stage growth of hydrous minerals after the peak metamorphic conditions and assemblage have been obtained.

The first retrogressive texture following peak metamorphism is observed in the high-grade gneisses. In the aluminous gneisses, post-kinematic coarse-grained, blocky muscovite encloses sillimanite prisms and biotite perpendicular to the foliation (Figure 22). Quantities of muscovite are low in these rocks, no greater than about 10%, but such a

Calc-silicates

System: $\text{SiO}_2\text{-CaO-MgO-H}_2\text{O-CO}_2$

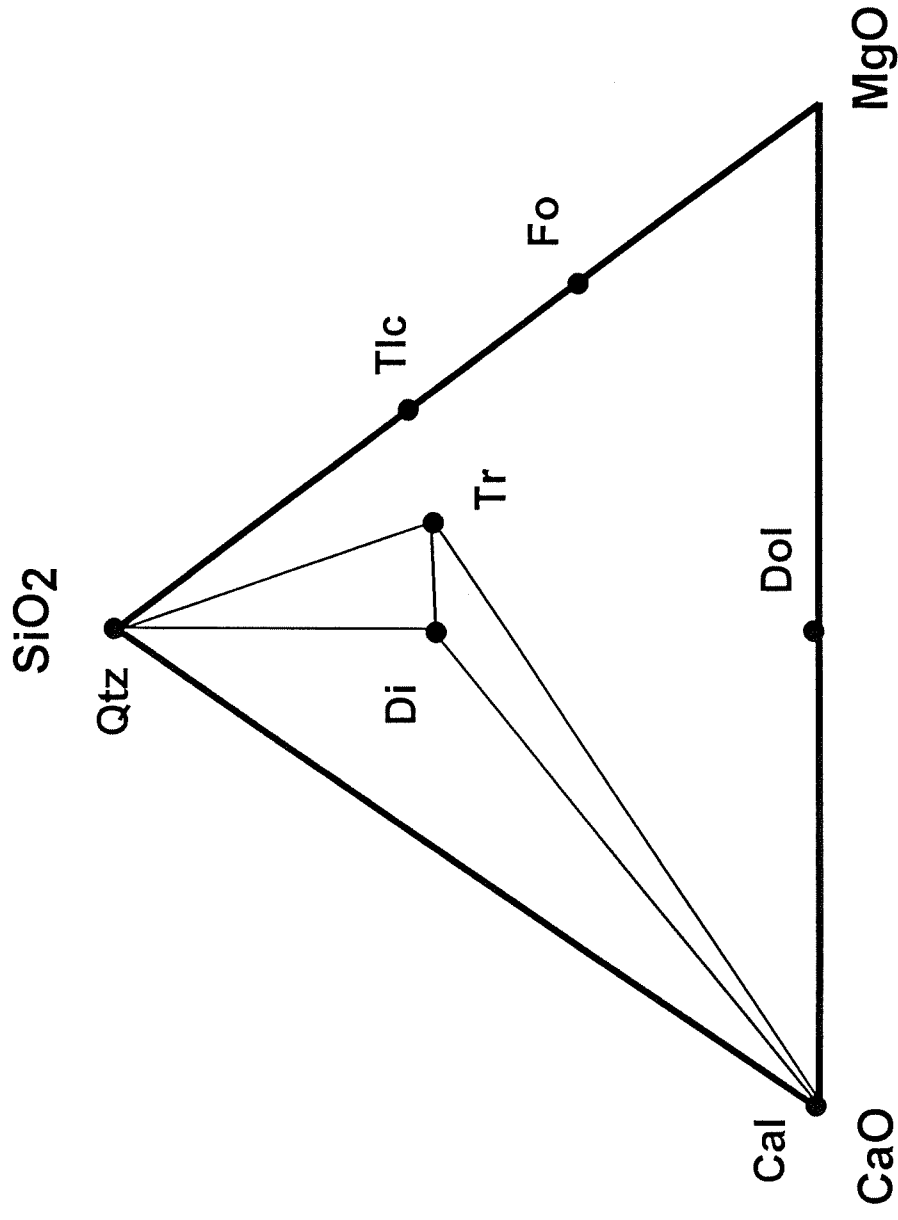


Figure 19: after Spear, 1993.

texture records the late stage growth of muscovite at lower than peak P-T and requires hydration of the rocks.

The mafic gneisses also contain mineral overprints. Cumingtonite overprints clinopyroxene as another indicator of an hydration event (Figures 8a, 8b). The hydration of plagioclase and resulting replacement by clinozoisite in its breakdown occurs in many of the amphibolites and all of the calc-silicates. Occasionally clinozoisite replaces clinopyroxene. In mafic rocks, epidote group minerals remain stable at intermediate pressures longer than at low pressures (Spear, 1993). In the Thompson Peak rocks, clinozoisite is present over a range of temperatures, ~500°-700° C and intermediate pressures, 5.2 to 7 kbars, in the retrograde path (Berman TWQ equilibria, applied by D. Henry). Figure 20 is an ACF presenting the amphibolite facies overprinting minerals, epidote (for clinozoisite), actinolite and cummintonite, and their relationships with the peak minerals such as garnet and plagioclase.

Amphibolites contain actinolite and cummingtonite overprints, growing by the hydration of clinopyroxenes (Figure 20). Actinolite represents an upper greenschist to amphibolite facies overprint with decreasing Al and Na (Spear, 1993); Na is a pressure indicator, therefore, decreases in Na suggest lowering pressures. The appearance of tremolite in the calc-silicates also represents a lower amphibolite facies overprint (Figures 14a, 14b; Spear, 1993) and indicates hydration by late stage fluids at these lower grades. Titanite after ilmenite utilizes Ca and Si released into the system as amphibole and plagioclase breakdown (Dutrow & Henry, pers. comm.; Figure 12). The growth of titanite may accompany the resetting (blue rims) of the amphiboles (Dutrow, pers. comm.;

Amphibolite Facies Overprint

System: $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-MgO-FeO-CaO-Na}_2\text{O-H}_2\text{O}$

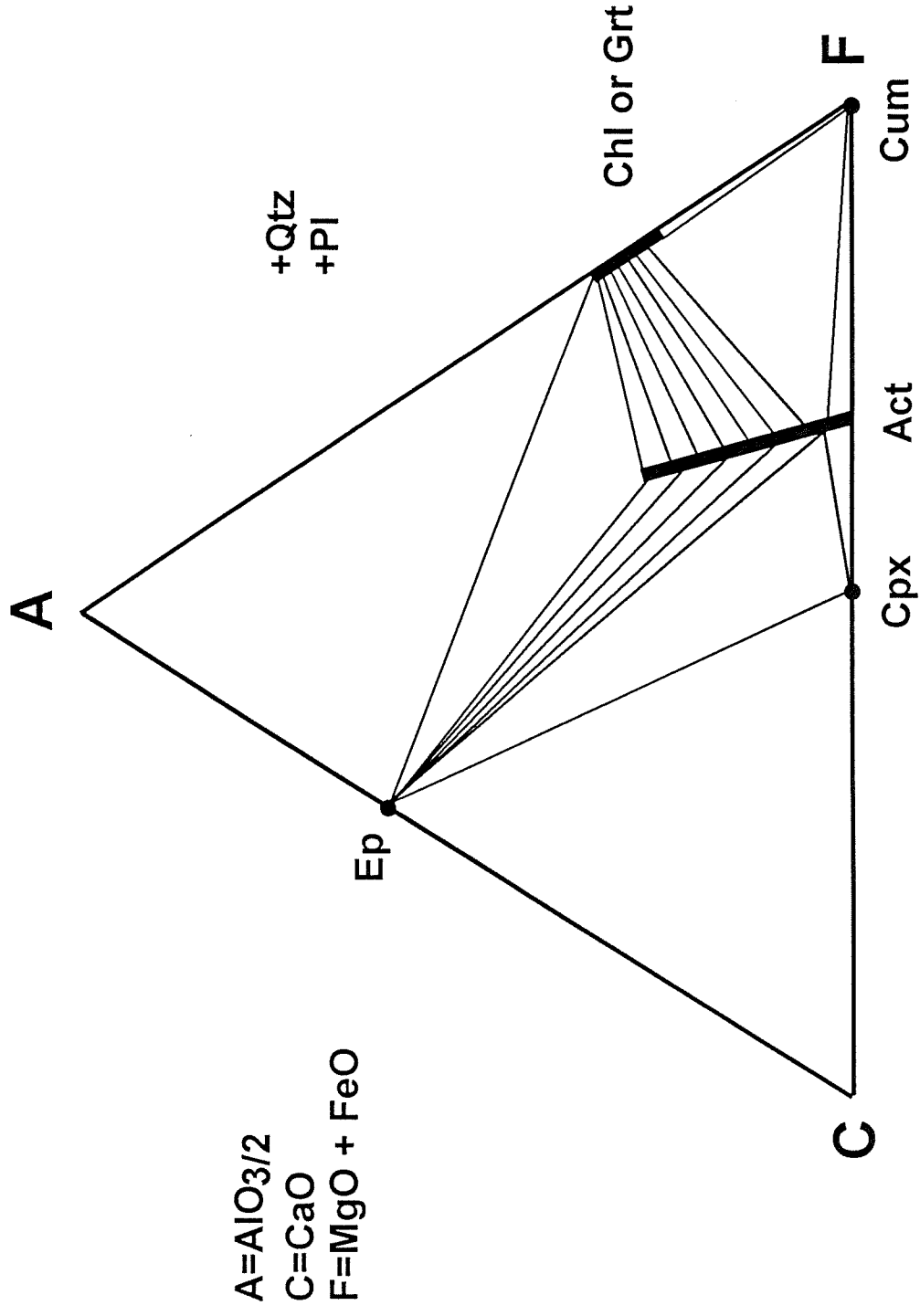
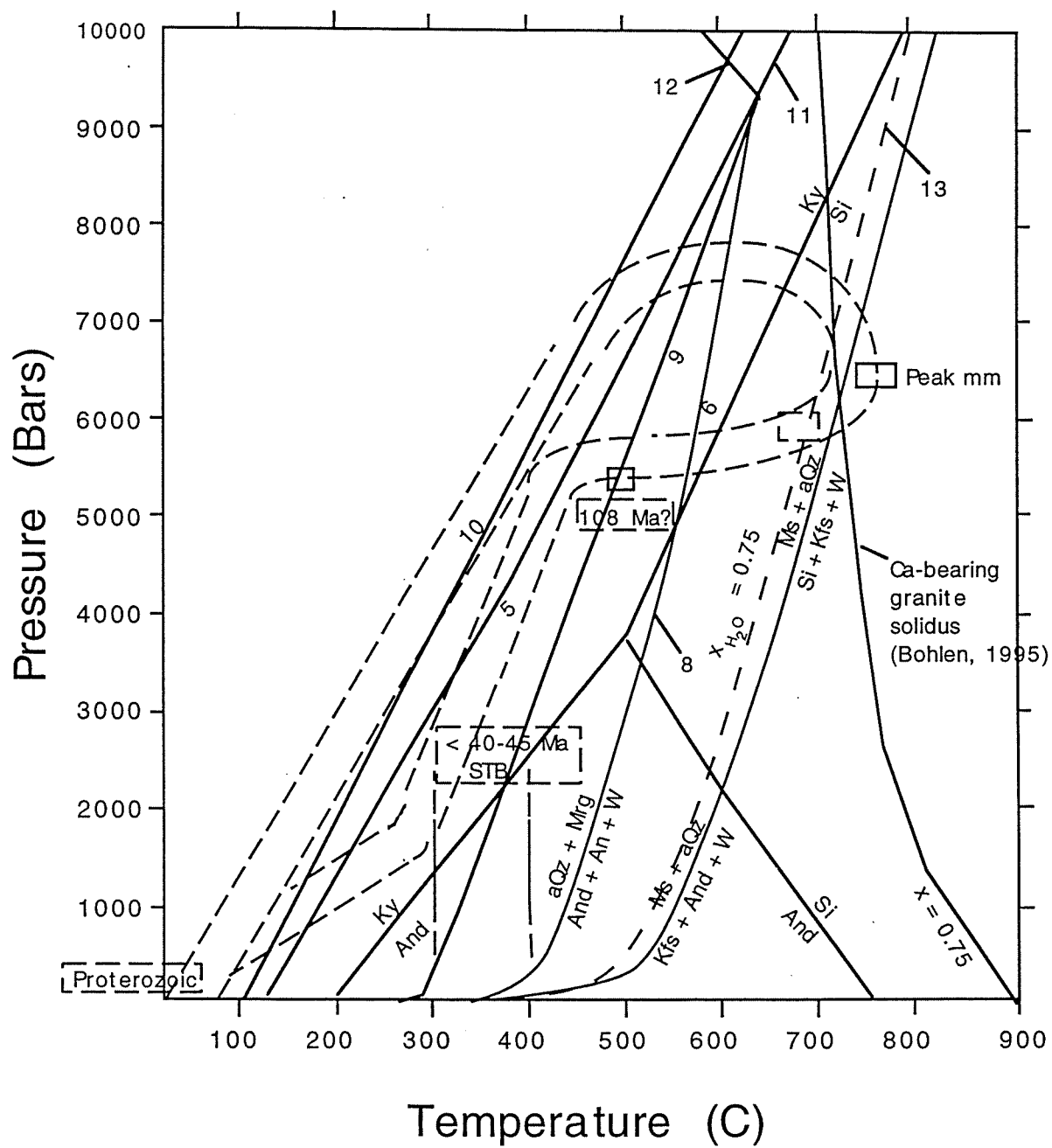


Figure 20: after Spear, 1993.



Currently being modified.

Figure 21 Petrogenetic Grid

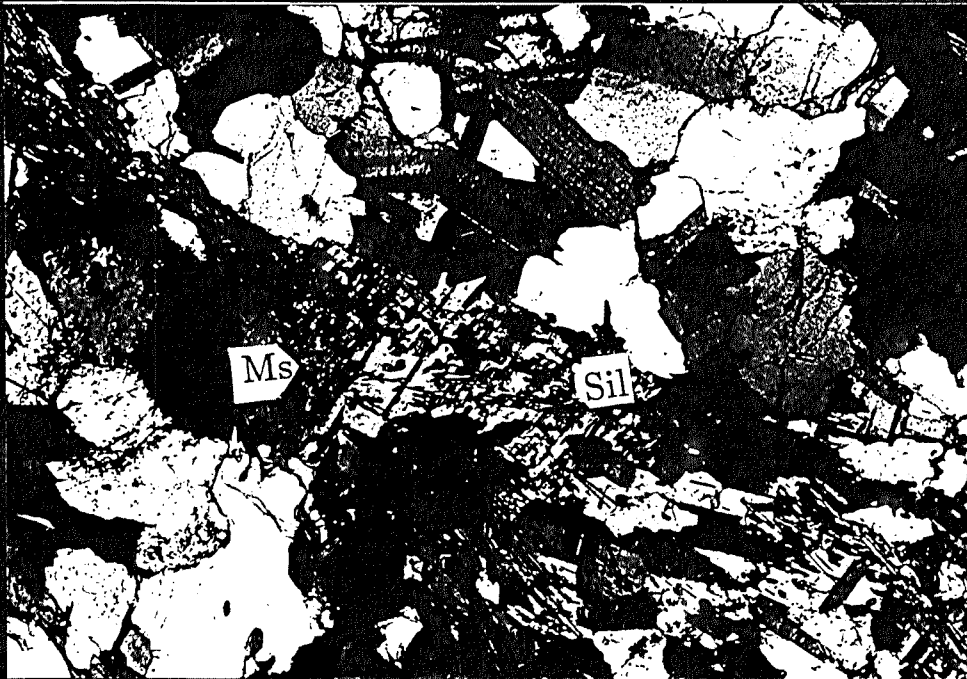
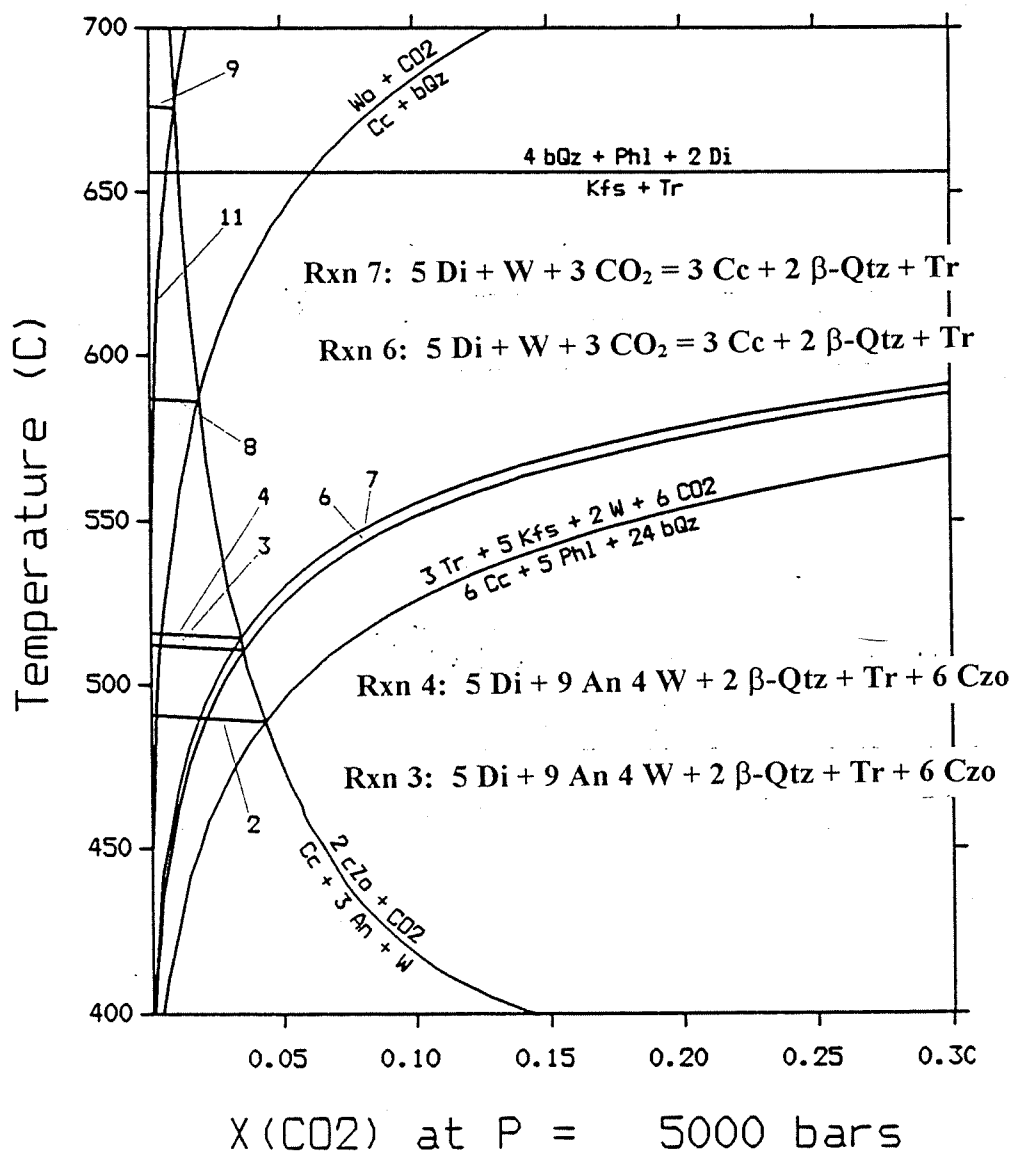


Figure 22: ST-95-08 Folded sillimanite-biotite gneiss. Ms overprint on sil & bio represents a retrograde reaction in the P-T path. Bio, qtz, pl, Fe-Ti oxides also present. (Crossed nicols. FOV=5.2mm)

Figure 10). The presence of these retrogressive minerals indicates stability fields through which the roof pendants travelled toward conditions of lower pressure and temperature.

Some grt-bio gneisses contain ms-mrg-zo pseudomorphs (Figures 9a, 9b). The overall prismatic or elongated morphology suggests that kyanite was the mineral pseudomorphed by the hydrous phases. Chemical analysis and geothermometry of the minerals in the pseudomorphs yields a temperature of $\sim 490^{\circ}\text{C}$ and a pressure of ~ 5.2 kbar (Berman TWQ equilibria applied by D. Henry; pers. comm.). The margarite stability field is a fairly restrictive one (D. Henry, pers. comm.) so the presence of margarite is a limiting factor on the P-T path of the roof pendants. Margarite is present, therefore, the retrograde path moved through the margarite stability field. The pseudomorphs were a result of fluid influx.

Application of Berman's PTX program (TWQ equilibria for XCO_2 , 1992) to the calc-silicates yielded reactions that restrict the possible temperatures and CO_2 content (based on mole fraction) for the influx of fluids in the roof pendants. Figures 23-25 show the important equilibria reactions for the appearance and disappearance of tremolite and clinozoisite, which are retrogressive minerals in the calc-silicates, at 5000 bars and 7000 bars. These calculations were made assuming that all mineral phases are pure endmember compositions. The results show that the fluid that infiltrated the calc-silicate rocks was low in CO_2 content, < 0.1 mole fraction (Figures 23-25). That means that the fluid must have been H_2O -rich or very nearly pure H_2O . The temperature regime determined by the intersections of the equilibria reactions restricts this infiltration to temperatures between 570°C and 625°C at 7000 bars. At 5000 bars the temperatures drop to approximately

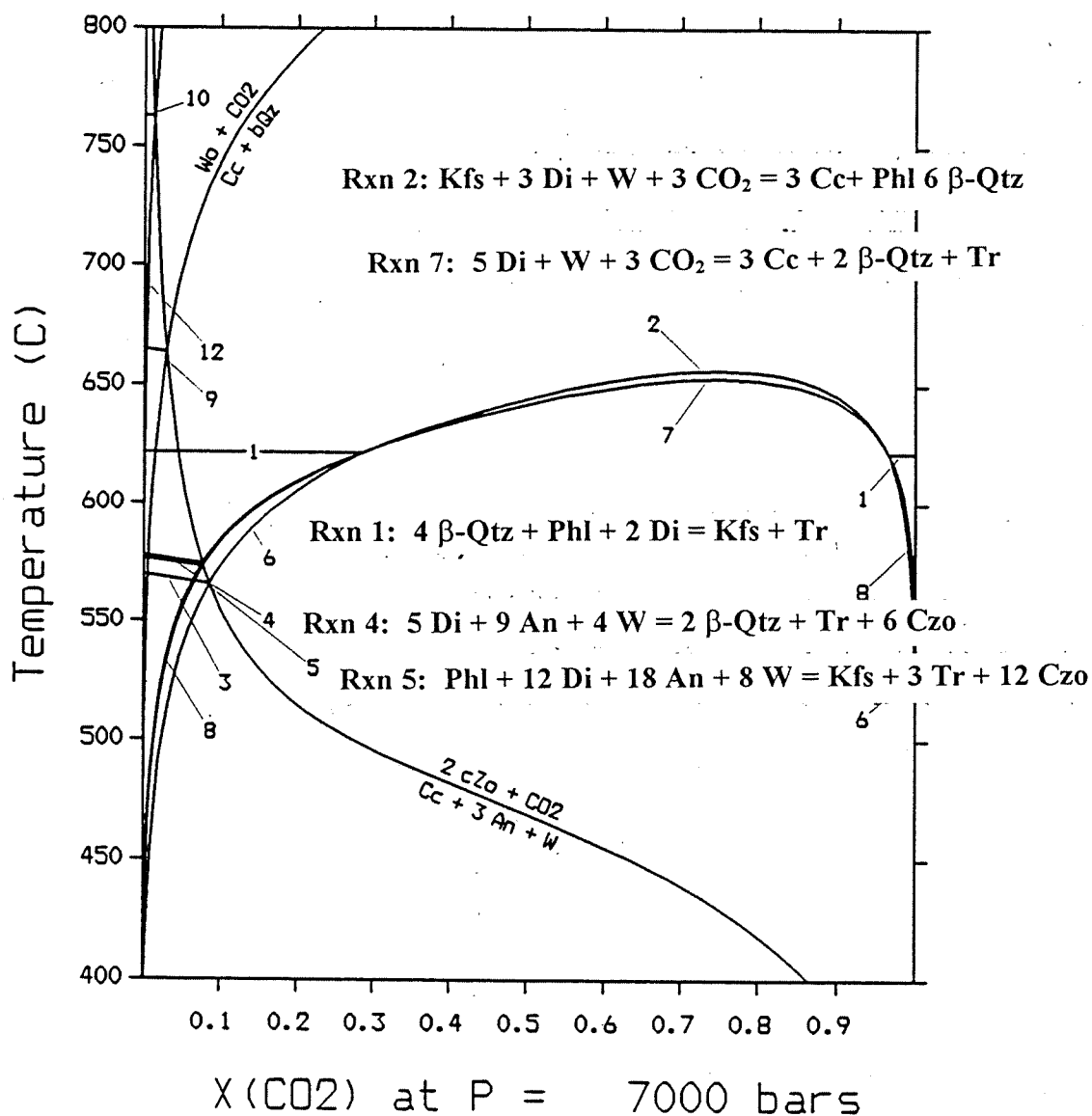


Reaction List Based on Calc-Silicates Mineral Assemblage:

pl + di + tr + czo + qtz + phl + ksp + cal + ttn + mgn + zr

- 1) 4 β-Qtz + Phl + 2 Di = Kfs + Tr
- 2) 3 Tr + 5 Kfs + 18 An + 8 W = 5 Phl + 24 β-Qtz + 12 Czo
- 3) 5 Di + 9 An 4 W + 2 β-Qtz + Tr + 6 Czo
- 4) Phl + 12 Di + 18 An + 8 W = Kfs + 3 Tr + 12 Czo
- 5) 3 Tr + 5 Kfs + 2 W + 6 CO₂ = 6 Cc + 5 Phl + 24 β-Qtz
- 6) 5 Di + W + 3 CO₂ = 3 Cc + 2 β-Qtz + Tr
- 7) Phl + 12 Di + 2 W + 6 CO₂ = 6 Cc + Kfs + 3 Tr
- 8) Wo + 3 An + W = β-Qtz + 2 Czo
- 9) 6 Wo + Phl + 9 An + 2 W = 3 Di + Kfs + 6 Czo
- 10) Wo + CO₂ = Cc + β-Qtz
- 11) 6 Wo + Phl + 3 CO₂ = 3 Cc + 3 Di + Kfs + W
- 12) 2 Czo + CO₂ = Cc + 3 An + W

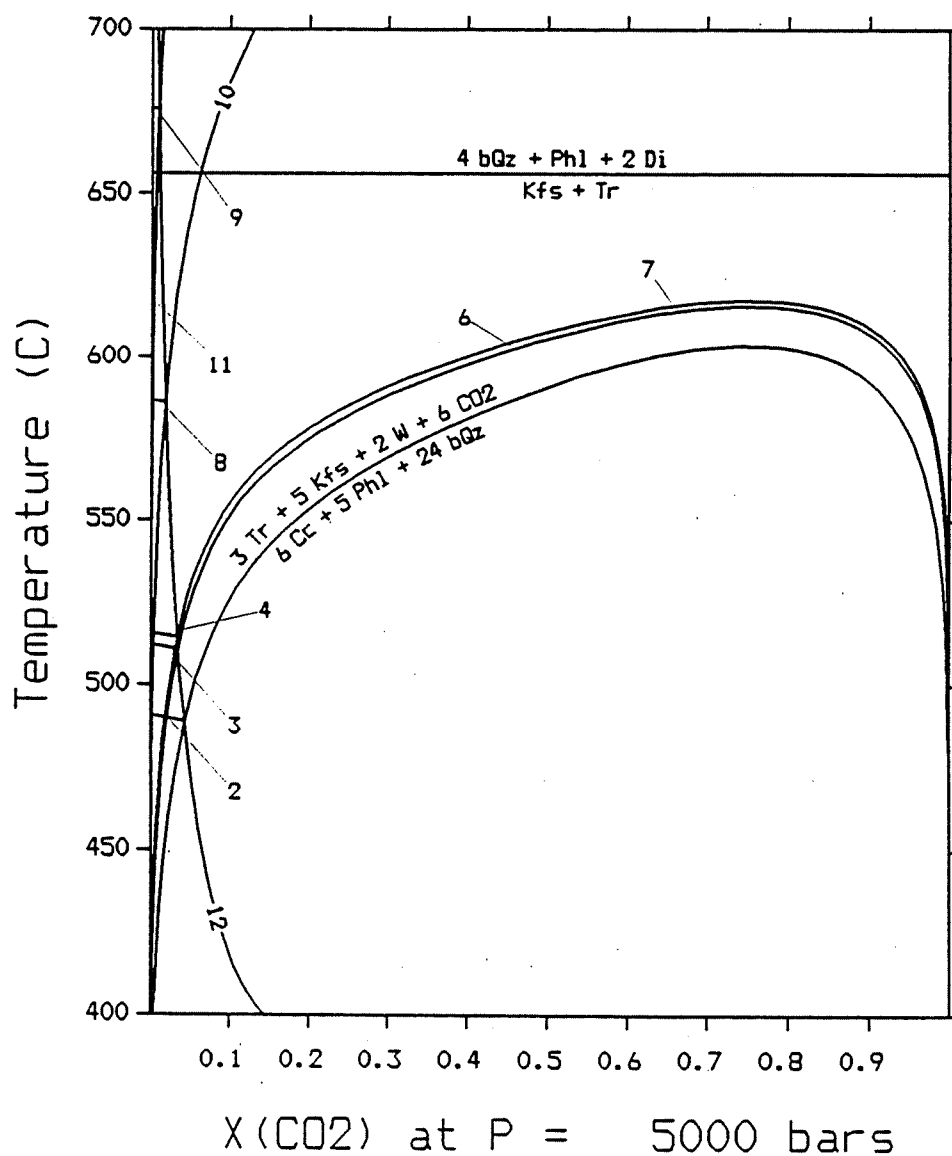
Figure 23



Reaction List Based on Calc-Silicates Mineral Assemblage: pl + di + tr + czo + qtz + phl + ksp + cal + ttn + mgn + zr

- 1) $4 \beta\text{-Qtz} + \text{Phl} + 2 \text{Di} = \text{Kfs} + \text{Tr}$
- 2) $\text{Kfs} + 3 \text{Di} + \text{W} + 3 \text{CO}_2 = 3 \text{Cc} + \text{Phl} + 6 \beta\text{-Qtz}$
- 3) $3 \text{Tr} + 5 \text{Kfs} + 18 \text{An} + 8 \text{W} = 5 \text{Phl} + 24 \beta\text{-Qtz} + 12 \text{Czo}$
- 4) $5 \text{Di} + 9 \text{An} + 4 \text{W} = 2 \beta\text{-Qtz} + \text{Tr} + 6 \text{Czo}$
- 5) $\text{Phl} + 12 \text{Di} + 18 \text{An} + 8 \text{W} = \text{Kfs} + 3 \text{Tr} + 12 \text{Czo}$
- 6) $3 \text{Tr} + 5 \text{Kfs} + 2 \text{W} + 6 \text{CO}_2 = 6 \text{Cc} + 5 \text{Phl} + 24 \beta\text{-Qtz}$
- 7) $5 \text{Di} + \text{W} + 3 \text{CO}_2 = 3 \text{Cc} + 2 \beta\text{-Qtz} + \text{Tr}$
- 8) $\text{Phl} + 12 \text{Di} + 2 \text{W} + 6 \text{CO}_2 = 6 \text{Cc} + \text{Kfs} + 3 \text{Tr}$
- 9) $\text{Wo} + 3 \text{An} + \text{W} = \beta\text{-Qtz} + 2 \text{Czo}$
- 10) $6 \text{Wo} + \text{Phl} + 9 \text{An} + 2 \text{W} = 3 \text{Di} + \text{Kfs} + 6 \text{Czo}$
- 11) $\text{Wo} + \text{CO}_2 = \text{Cc} + \beta\text{-Qtz}$
- 12) $6 \text{Wo} + \text{Phl} + 3 \text{CO}_2 = 3 \text{Cc} + 3 \text{Di} + \text{Kfs} + \text{W}$
- 13) $2 \text{Czo} + \text{CO}_2 = \text{Cc} + 3 \text{An} + \text{W}$

Figure 24



Reaction List Based on Calc-Silicates Mineral Assemblage:

pl + di + tr + czo + qtz + phl + ksp + cal + ttn + mgn + zr

- 1) 4 β -Qtz + Phl + 2 Di = Kfs + Tr
- 2) 3 Tr + 5 Kfs + 18 An + 8 W = 5 Phl + 24 β -Qtz + 12 Czo
- 3) 5 Di + 9 An + 4 W + 2 β -Qtz + Tr + 6 Czo
- 4) Phl + 12 Di + 18 An + 8 W = Kfs + 3 Tr + 12 Czo
- 5) 3 Tr + 5 Kfs + 2 W + 6 CO₂ = 6 Cc + 5 Phl + 24 β -Qtz
- 6) 5 Di + W + 3 CO₂ = 3 Cc + 2 β -Qtz + Tr
- 7) Phl + 12 Di + 2 W + 6 CO₂ = 6 Cc + Kfs + 3 Tr
- 8) Wo + 3 An + W = β -Qtz + 2 Czo
- 9) 6 Wo + Phl + 9 An + 2 W = 3 Di + Kfs + 6 Czo
- 10) Wo + CO₂ = Cc + β -Qtz
- 11) 6 Wo + Phl + 3 CO₂ = 3 Cc + 3 Di + Kfs + W
- 12) 2 Czo + CO₂ = Cc + 3 An + W

Figure 25

480°C to 530°C for the stability of clinozoisite and tremolite. Application of the Berman TWQ equilibria (D. Henry, pers. comm.), yielded a temperature of approximately 490°C at a pressure of 5300 bars for the formation of the ms-mrg-zo pseudomorphs in the pelitic gneisses. The formation of the pseudomorphs coincides with the overprinting of clinozoisite and tremolite in the calc-silicates. These calculations are further evidence of a fluid phase influx under lower amphibolite facies conditions.

A mylonitization event effected not only the calc-silicates but the quartzites, marbles and gneisses as well. The range of conditions for mylonitization is poorly constrained at approximately 300°-400° C and pressures below 3 kbars (Dutrow & Henry, pers. comm.). This range generally marks the transition zone from brittle to ductile deformation in the crust. Petrographic evidence of both ductile and brittle deformation exists in the calc-silicates. The rocks display brittle-ductile deformation to varying degrees in feldspars, pyroxene and quartz. Pyroxene and plagioclase behave brittly while quartz exhibits ductile behavior (Figure 15). Cataclasis of grains, grinding and reduction to smaller grain sizes (e.g., Williams et al, 1982), is observed in the gneisses as well as in the calc-silicates.

The preliminary P-T path of the roof pendants is sketchy at best at this time. However, important markers of metamorphic grade and fluid contact have been observed and utilized to estimate the P-T history of the metamorphic rocks. Some chemical data aids in that estimation. Microprobe analyses (by D. Henry) of garnet and plagioclase in the roof pendant rocks reveal that the Ca content of both minerals does not change, or that compositional resetting does not occur in them. This impacts the P-T path in that I

forces it to follow along a steep slope, to follow the isopleths (curves of constant K_D or composition). If the Ca content of these minerals had changed over time, the path would have crossed the isopleths accordingly and varied the slope of the curve. This information helps to define slightly more accurately the direction the retrograde path takes.

CONCLUSIONS: THE METAMORPHIC HISTORY OF THE ROOF PENDANTS

The history of the Thompson Peak roof pendants begins with the deposition of miogeoclinal sediments in the Proterozoic. Sm/Nd analyses on zircons (by Paul Mueller, Univ. of Florida) from the metamorphic rocks reveal ages from 1.8 Ga to 2.3 Ga. The rocks followed a prograde path that moved through the kyanite stability field, as shown in the petrogenetic grid (Figure 21). Temperatures of $\sim 795^\circ\text{C}$ and pressures of 7.2 kbars suggest that the Thompson Peak roof pendants were buried to depths of 20-25 km into the lower crust. These P-T conditions are the peak metamorphic conditions for the roof pendants. Upon uplift in the Laramide orogeny, the rocks began their retrograde path. Two hydration events occurred in the retrograde path. The first is marked by the appearance of muscovite at upper amphibolite facies conditions. The second hydration event is evidenced by the pseudomorphs in the pelitic gneisses and the tremolite and clinozoisite overprinting in the calc-silicates at conditions of lower amphibolite facies metamorphism. The timing of these hydration events is unknown. However, it is possible that hydration occurred simultaneously with the Idaho Batholith intrusion into the Precambrian metamorphic rocks. A mylonitization event occurred at much shallower depths, approximately 5-10 km (B. Dutrow & D. Henry, pers. comm.). It is uncertain as

to the correlation of the mylonitization to the Sawtooth Batholith intrusion. Retrogressive metamorphism continued until the rocks were exposed at the Earth's surface. Pleistocene glaciation provided the topography observed today in the Sawtooth Mountain Range. Though the historical events marking this path are only snapshots of the metamorphic history of the roof pendants, this preliminary P-T path of the Thompson Peak roof pendants provides valuable information regarding the development of the Sawtooth Mountains.

Through study of mineral assemblages and textures and application of geothermobarometric techniques, our knowledge of the evolution of the Earth's crust is advanced. Study of the correlation of the Precambrian roof pendants in Idaho to the rocks of surrounding regions is enhanced by this petrologic study. The tectonic implications derived from petrologic studies of the Thompson Peak metamorphic rocks in the Sawtooth Mountains of south-central Idaho can be incorporated into the existing knowledge of the developmental history of the Precambrian North American craton.

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