Structure of Archean Marbles of the Indian Creek Metamorphic Suite, Tobacco Root Mountains, Southwestern Montana

Carlos M. Picornell
Department of Geology and Geophysics, University of New Orleans, New Orleans, LA 70148
Faculty Sponsor: Terry Pavlis, University of New Orleans

INTRODUCTION

The Indian Creek Metamorphic Suite (ICMS) in the Tobacco Root Mountains of Southwestern Montana is characterized by abundant marbles. The abundance of marbles in the ICMS is unlike the other metamorphic suites, Sphuler Peak Metamorphic Suite (SPMS) and Pony - Middle Mountain Metamorphic Suite (PMMMS). The ICMS carbonates are associated with isoclinal, gently inclined to overturned folds. These folded carbonates are exposed in the west-central region of the range, and due to their resistance, the carbonates serve as good markers that define the shape and attitude of the folds (Burger, 1966). These folds are inferred to be the earliest recognizable folding in the region produced during the main penetrative deformational event (Brady et al,1996). This deformational event (S1) produced the dominant foliation observed in the Tobacco Root Archean rocks. This deformation may have occurred during the initial Precambrian deformation event that occurred at 2.7 Ga (Mueller and Cordua, 1976; James and Hedge, 1980). Due to their presence and resistance to weathering, the marbles may yield information on the region's deformation history. With that in mind, the purpose of this study is to understand the structural orientation of the marbles of the ICMS and its relationship to the SPMS.

ICMS STRUCTURAL FIELD OBSERVATIONS

The mesoscopic folds common to the ICMS and west-central regions of the Tobacco Root Mountains are sequences of upright, sub-isoclinal folds that plunge gently to the north-northwest, north, or north-northeast at gentle angles, and are dominated by folds with west dipping axial surfaces (Brady et al, 1996). Brady et al. (1996) state that these structures distinctly deform the dominant foliation developed by earlier recumbent folds of the region. Thus, assuming the main fabric is the earliest deformation, these superimposed folds are referred to here as F2. The ICMS outcrop scale folds range in style from open-to-close, concentric folds to tight-to-isoclinal similar folds. A majority of these folds are cylindrical in nature at outcrop scale, yet at large scale linear folds axes are scattered implying curved fold axes and macroscopic non-cylindrical folds (Brady et al, 1996). One possibility for the non-cylindrical fold geometry is sheath folding. Sheath folds are described by strongly curved fold axes that form a scattered great circle distribution (Mies, 1991) . These patterns have been seen in the region and interpreted as characteristic of simple shear deformation (Harms et al, 1996). Brady et al (1996) add that the scattered fold axis pattern is diverted by outcrop-scale third-generation, broad, open folds and if simple shear related sheath folds exist in the ICMS of the Tobacco Roots, it predate the last period of folding.

METHODS AND ANALYSIS

Total Station and 3-point problems. To better understand the structural geometry and orientation of the map scale folds in ICMS marble marker horizons, a total station was used to survey a series of strategic points along lithologic layering of fold limbs in three areas. Those three areas were Horse Creek, Mill Creek and Quartz Creek. The results gathered were used to construct six three-point problems. In addition, several foliation attitude measurements were taken and recorded from Horse, Mill and Quartz Creeks and Leggat Ridge. These measurements were applied to the study.

Station markers were placed along the contact between marble and ICMS quartzofeldspathic gneisses. A minimum of three station markers were measured for each fold limb. The purpose of the total station is to accurately measure the orientation of marble beds in the ICMS. Some three-point problem results were analyzed both graphically and mathematically through Excel spreadsheets. In addition, all fold results were plotted with Stereonet 4.9 (Allmendiger, 1995). Due to lack of recorded total station information, the Horse Creek fold was only analyzed graphically. The Quartz Creek fold was analyzed graphically, but could be recalculated analytically. The Mill Creek fold was initially analyzed graphically, but due to the tight survey area and relatively steep dip of one limb, it was prone to error. As a result, the Mill Creek fold was analyzed mathematically.

Total Station Results. The total station results show that the Horse Creek eastern fold limb dips shallowly to the west, while the western fold limb dips shallowly to the east (Figure 1; Figure 2). The Horse Creek fold has an

The chemical homogeneity of garnets is a result of volume diffusion which starts to occur at temperatures greater than 650°C, at or above the sillimanite isograd (Tracy et al., 1976). Since growth zoning has been completely obliterated in large garnets, temperatures at or above 650°C must have persisted for an extended period of time. The slight increase in almandine percent in garnet and increase in phlogopite (Mg end-member) percent in biotite at grain boundaries is indicative of a disequilibrium response to rapid retrograde cooling from granulite grade temperatures (Lasaga et al., 1977). Thus, rapid cooling occurred at some point in the P-T evolution of the rocks.

Evidence for decompression exists in a few samples from the SPMS. Sample TBR-133 of the SPMS shows a rim of cordierite and spinel around garnet which indicates isothermal decompression (Spear, Kohn, and Cheney, in review). This rim was created by the reaction:

garnet + sillimanite = cordierite + spinel (Spear, Kohn, and Cheney, 1998, in review)

Cordierite and spinel are intergrown outside of the garnet grains. Sample KAT-41, also from the SPMS, shows sillimanite pseudomorphs of kyanite which has been interpreted as evidence for isothermal decompression (Cheney et al., 1994). The absence of these retrograde textures in the ICMS may be due to the loss of melt products from the rock. The loss of melt not only changes the bulk composition, it also takes away the water component necessary for retrograde metamorphism to be recorded (Spear, Kohn, and Cheney, 1998, in review).

CONCLUSIONS

Pelites from the ICMS and SPMS record a high pressure, high temperature metamorphic event that caused partial melting and the development of restites. A few samples record a later-stage decrease in pressure which implies a clockwise P-T-t path for the SPMS. If earlier, high pressure and temperature assemblages in both units are recording the same event, it is likely that the ICMS also underwent isothermal decompression but did not record the conditions (much like many of the SPMS rocks) due to change of bulk composition and absence of water caused by the removal of melted pelites from the system. If P-T-t evolution is the same for both units, it is likely that the units were juxtoposed prior to the recorded metamorphic event. The presence of metamorphosed dikes and sills (MMDS) in the ICMS and not the SPMS makes juxtaposition prior to the earlier metamorphic events unlikely. Thus, the metamorphic event recorded by the pelites is likely to have occurred at 1.8 Ga.

REFERENCES CITED

Cheney, John T., Brady, John B., Burger, H. Robert, King, Jonathan T., Tierney, Kara A., Peck, William H., Poulsen, Chris J., Cady, Pamela, Lowell, Josh, Sincock, Mary J., Archeleta, LeAndra L., Fisher, Robin, and Jacob, Lisa, 1994, Metamorphic evolution of Archean rocks in the Tobacco Root Mountains of S.W. Montana: Geological Society of America Abstracts with Programs, v. 26, p. A-226.

James, H.L., and Hedge, C.E., 1980, Age of basement rocks of southwestern Montana: Geological Society of America Bulletin, v. 91, p. 11-15.

Lasaga, A. C., Richardson, S. M., and Holland, H. C., 1977, Mathematics of cation diffusion and exchange between silicate minerals during retrograde metamorphism. *In* Saxena, S. K., and Bhattacharji, S., Eds., *Energetics of Geological Processes*, 353-388, Springer-Verlag, Berlin.

Mueller, Paul, Wooden, Joseph L., Mogk, David W., Nutman, Allen P., 1996, Extended History of a 3.5 Ga Trondhjemitic Gneiss, Wyoming Province, USA: Evidence from U-Pb Systematics in Zircon, Precambrian Research, 78, 41-52.

Spear, Frank S., Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths. Washington, D.C: Mineralogical Society of America, 1993.

Spear, Frank S., Kohn, Matthew J., and Cheney, John T., 1998, P-T paths from anatectic pelites: currently in review.

Tracy, R. J., Robinson, P., and Thompson, J. B. Jr., Garnet composition and zoning in teh determination of temperature and pressure metamorphism, central Massachusetts. American Mineral. 61, 762-775.

Vitaliano, C.J., Burger, H. R., Cordua, W. S., Hanley, T. B., Hess, D. F., and Root, F. K., 1979, Explanatory text to accompany the geologic map of the southern Tobacco Root Mountains, Madison County, Montana: Geological Society of America Map and Chart Series MC-31, 8 p.

Vitaliano, C.J., Kish, S.A., and Towell, D.G., 1976. K-Ar dates and Sr isotopic values for rocks of the Tobacco Root batholith: Isochron/West, v. 28, v. 13-15.

interlimb angle of 75 degrees, classifying the fold as a open synform. The Quartz Creek eastern fold limb dips gently to the east and, in addition, the western fold limb dips steeply to the west. The Quartz Creek fold has interlimb angle of 67 degrees, classifying the fold as a close, isoclinal antiform. The Mill Creek eastern fold limb dips gently to the west, while its western limb dips steeply to the west. The interlimb angle of the Mill Creek fold is 48 degrees and is classified as a close fold.

Stereonet Results. Foliation measurements from the field were plotted with Stereonet 4.9. Poles to foliation and best fit girdles were plotted to the measurements (Figure 3). The pole to the girdle is generally inferred to be the axis of the marble fold. The foliation poles suggest that the fold axis of the Horse Creek and Quartz Creek folds plunges shallowly to the north. In contrast, Mill Creek and Leggat Ridge poles indicate its fold axes plunges shallowly NNE. The Eigenvector calculations from Stereonet 4.9 show a high first eigenvector value, an intermediate eigenvector second value, and low third eigenvector value. This low third eigenvector values indicates a non-random fold axis distribution. (McEachran, 1990). Nonetheless, the data show significant scatter and the foliation measurements imply some variance from a cylindrical geometry.

DISCUSSION AND INFERENCES

Fold axes measurements indicate that the marble structures are cylindrical folds plunging shallowly to the north-northeast. In addition, foliation pole measurements indicate that the ICMS experienced similar deformation episode(s) and direction. The geometry of folding inferred from the total station results indicate that the major macroscopic folds in the study area are a series of open to close, upright to steeply inclined, gently plunging folds. This result is consistent with the general map pattern of lithologic units in the ICMS (Burger, 1966; Vitaliano et al, 1979) which form a general zigzag pattern suggestive of simple, upright structures. Because these structures deform the main foliation and lithologic layering, they are clearly younger than the main metamorphic foliation (S1) in the ICMS. Based on orientation (upright axial surface), these folds are probably F2 or F3 structures of Burger (1966).

The cylindrical folds of the ICMS do not support the extension of the proposed sheath fold in the SPMS into the ICMS (Owen, 1996) unless the sheath fold structures are transposed in the main foliation. The marble cylindrical fold axes plunge north and intersect with the sheath fold long axis (maximum elongation direction) plunging to the NNW (Owen, 1996). The ICMS/ SPMS contact and several regions of the SPMS such as Sphuler Ridge, Sphuler Peak and Mustard Pass contain lineation orientations (King, 1994; Kranenburg, 1996; Owen, 1996) that are concordant to the north, northeast plunge direction of the ICMS marble fold axes, although the fold style is distinct from the ICMS.

A speculation for such variability of structures between adjacent units may be the existence of an earlier metamorphic unit (SPMS) prior to the S1 deformation. During the S1 metamorphic event, the older structures in the SPMS may have been subjected to deformation and rotation. Such rotation could explain variable discordance and concordance present between the ICMS and SPMS, and, possibly, such structures may resemble the presence of a sheath fold.

REFERENCES CITED

Allmendiger, R.W., 1995, Stereonet Version 4.9: a plotting program for orientation data for the Macintosh Computers.

Brady, J.B., Burger, H.R., and Cheney, J.T., 1994, Archean rocks of the Tobacco Root Mountains, Montana, In: Wilson, M.A., (ed), The Seventh Keck Research Symposium in Geology Abstract Volume, p.54-59.

Brady, J.B., Burger, H.R., Cheney, J.T., Harms, T.A., Johnson, K.E., 1996, Geochemistry, petrology and structure of Archean rocks, Tobacco Root Mountains, southwestern Montana, In: Wilson, M.A., (ed), The Ninth Keck Research Symposium in Geology Abstract Volume, p.54-59.

Burger, H.R., 1966, Structure, petrology, and economic geology of the Sheridan district, Madison County, Montana (Ph.D. thesis): Bloomington, Indiana, Indiana University, 156, p.

Harms, T.A., Burger, H.R., Brady, J.B., Cheney, J.T., Johnson, K.E., Owen, D.R., King, J.T., Kranenburg, S., Sincock, M.J. and Lowell, J. 1996, Structural setting of Archean rock suites in the Tobacco Root Mountains, southwestern Montana; Geological Society of America Abstracts with Programs, v. 28, p. A-245.

James, H.L., and Hedge, C.E., 1980, Age of basement rocks of southwestern Montana: Geological Society of America Bulletin, v. 91, p. 11-15.

King, J.T., 1994, Structural relationships among Archean gneisses in the Tobacco Root Mountains, Southwestern Montana (B.A. thesis): Amherst, Massachusetts, Amherst College.

Kranenburg, S.R., 1996, Structural Relationships among Metamorphic Suites in the Tobacco Root Mountains, Kranenburg, S.R., 1996, Structural Relationships among Metamrophic Suites in the Tobacco Root Mountains, southwestern, Montana (B.A. Thesis): Huntsville, Texas, Sam Houston State University .

McEachran, D.B., 1990, Stereo: the stereographic projection projection program for the Macintosh.

Mies, J.W., 1991, Planar dispersion of folds in ductile shear zones and kinematic interpretation of fold-hinge girdles: Journal of Structural Geology, Vol. 13., No.3, p 281-297.

Mueller, P.A., and Cordua, W.S., 1976, Rb-Sr whole-rock ages of gneisses from the Horse Creek area, Tobacco Root Mountains, Montana: Isochron/West, v. 16, p. 33-36.

Owen, D.R., 1996, Archean Deformation of the Tobacco Root Mountains, southwestern Montana (B.A. Thesis): Amherst, Massachusetts, Amherst College.

Reid, R.R., 1957, Bedrock of geology of the north end of the Tobacco Root Mountains, Madison County, Montana: Montana Bureau of Mines and Geology Memoir 36, 25 p.

Vitaliano, C.J., Burger, H.R., Cordua, W.S., Hanely, T.B., Hess, D.F., and Root, F.K., 1979, Explanatory text to accompany the geologic map of the southern Tobacco Root Mountains, Madison County, Montana: Geologic Society of America Map and Chart Series MC-31, 8 p.

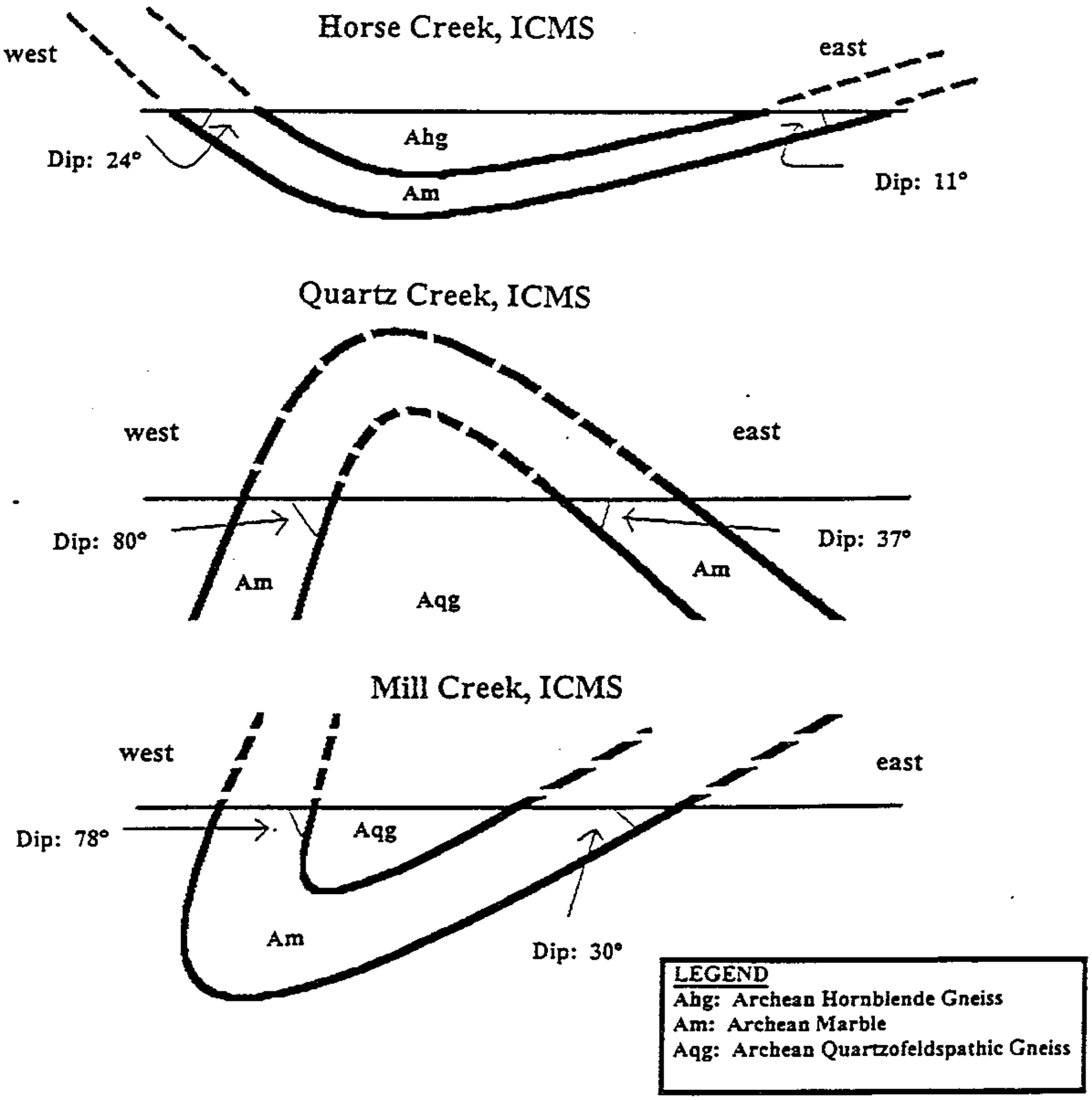
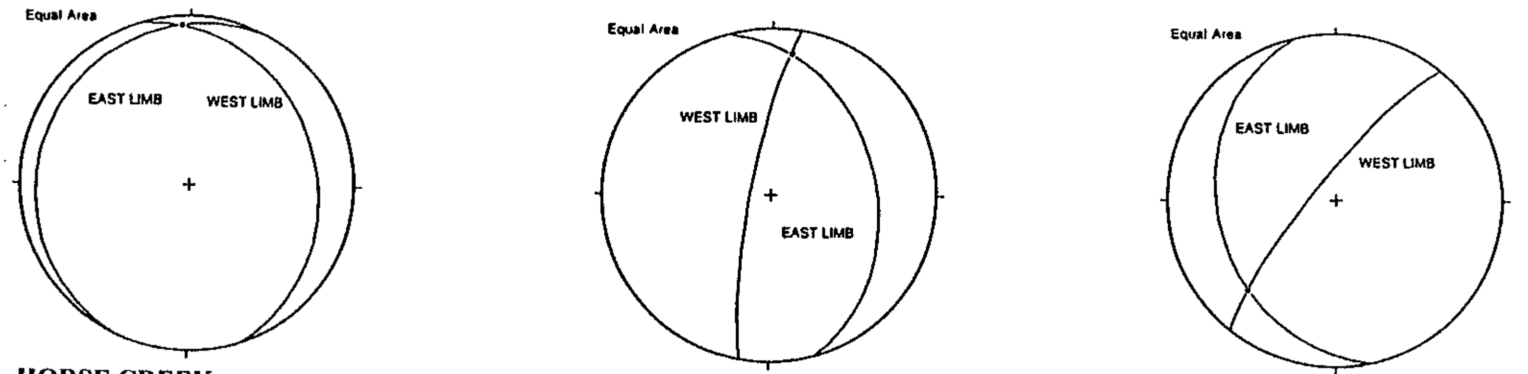


Figure 1. Schematic West - East cross sections of ICMS study areas. Figures are not to scale.



HORSE CREEK

West Limb	East Limb
Strike: 343	Strike: 026
Dip: 24 W	Dip: 11 E

POINT OF INTERSECTION
Trend: 357 Plunge: 6 N

QUARTZ CREEK

West Limb	East Limb
Strike: 010	Strike: 345
Dip: 80 W	Dip: 37 E

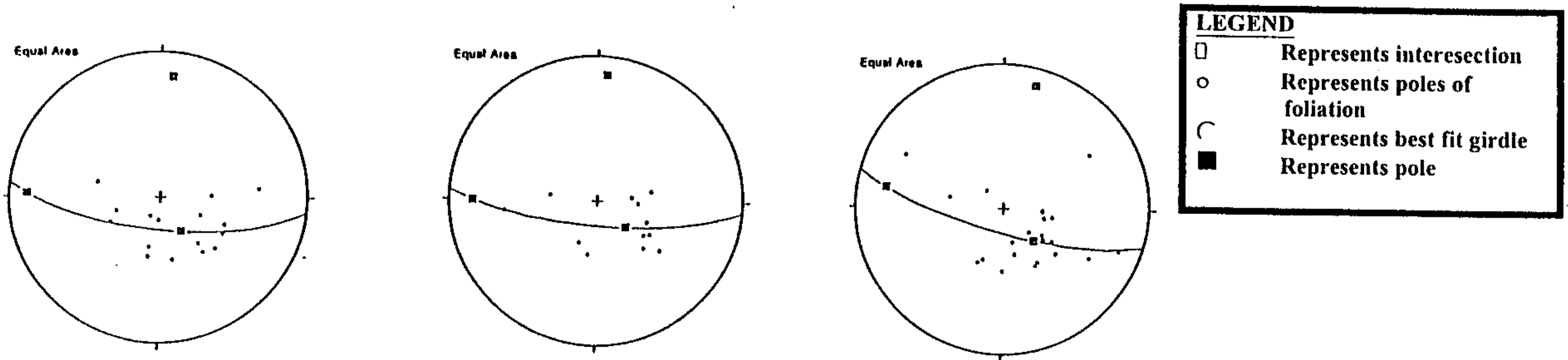
POINT OF INTERSECTION
Trend: 008 Plunge: 14 N

MILL CREEK

West Limb	East Limb
Strike: 039	Strike: 346
Dip: 79 W	Dip: 30W

POINT OF INTERSECTION
Trend: 224 Plunge: 26 N

Figure 2. Lower hemisphere projection of marble fold axis orientations in the ICMS determined from total station problem analysis of the orientation of two limbs of each fold. Intersection of girdles represents fold axis.



HORSE CREEK
Trend: 005 Plunge: 10 N

QUARTZ CREEK
Trend: 003 Plunge: 8 N

MILL CREEK
Trend: 15 Plunge: 8 N

Figure 3. Lower hemisphere projection of foliation in ICMS. Pole to best fit girdle represents the local fold axis.

Geothermobarometry of Archean garnet-amphibolites: Pony-Middle Mountain and Spuhler Peak Metamorphic Suites, Tobacco Root Mountains, southwest Montana

Kurt J. Steffen
Department of Geology, Carleton College, 300 North College St. Northfield, MN 55057
Faculty Sponsors: Professor Bereket Haileab, Carleton College

INTRODUCTION AND PURPOSE

The Tobacco Root Mountains of southwest Montana are exposed as an easterly tilted block uplift related to Laramide effects. The Pony-Middle Mountain (PMMMS), Spuhler Peak (SPMS) and Indian Creek (ICMS) metamorphic suites comprise the three Archean rock packages which form the core of the range (Vitaliano *et al.*, 1979). The PMMMS is dominated by quartzofeldspathic gneiss with lesser amounts of mafic gneiss and minor amounts of quartzite and marble. Previous Keck workers (Jacob, 1994; Wegmann, 1996) concluded that the gneisses of the ICMS and PMMMS have a dominantly igneous parentage. However, work by Cordua (1973) and the presence of marble and quartzite within these units indicate some sedimentary contribution to the protolith. The PMMMS and ICMS originated in a stable continental shelf setting (Brady *et al.*, 1994). Previous geochemical work by Sincock (1994) and Poulson (1994) indicates that the SPMS originated as tholeittic basalt. The presence of orthoamphibole-bearing amphibolite as well as hornblende amphibolites, quartzites and marbles is consistent with an oceanic origin for the SPMS. Metamorphosed Mafic Dikes and Sills (MMDS) occur in the PMMMS and ICMS within two feet of the contact between these two units and the SPMS. MMDS are never found within the SPMS. The PMMMS and SPMS have different origins (continental vs. oceanic) and have undergone a different tectonic history (the presence of MMDS in the PMMMS); however, they are found in contact today.

Amphibolite grade metamorphism dominates the range. However, relict high P garnet cores, surrounded by low P (OPX-plag) assemblages, and localized melt textures indicate that granulite grade metamorphism was attained locally (Degraff, 1996). Rb/Sr dates at 2.6 Ga, zircon overgrowth at 2.4 Ga and zircon core dates at 3.3 Ga (Krogh *et al.*, 1997) may all be associated with relict high P (~10Kb), granulite events. The $^{40}Ar/^{39}Ar$ system was reset during a lower pressure, amphibolite (P<6Kb) thermal event at 1.7-1.8 Ga which was insufficient to reset the U/Pb or Rb/Sr systems (Kovaric *et al.*, 1996).

Field relations support the following chronology: 1) Formation of gneissic banding within the PMMMS; 2) Intrusion of MMDS into the PMMMS and ICMS; 3) Juxtaposition of continental (ICMS and PMMMS) and oceanic crust (SPMS); 4) All terranes were subsequently deformed and metamorphosed together. The purpose of this study is to petrographically analyze the same lithology and assemblage to determine at what point these units began to share the same metamorphic history.

METHODS:

Nine samples, five from the PMMMS and four from the SPMS, were analyzed using Amherst College's Zeiss Digital Scanning Electron Microscope and Link Energy Dispersive Spectrometer. Point traverses and x-ray maps for Ca, Mn, Fe and Mg were created for eight samples and elucidate the nature of the zoning in the garnets. Kohn and Spear's Thermobarometry 2.0 program was used to apply Graham and Powell's (1984) garnet+ hornblende geothermometer and Kohn and Spear's (1990) garnet+ hornblende+ plagioclase+ quartz geobarometer using the Tschermakite-Mg calibration.

RESULTS:

Amphibolites from both units contain the assemblage hornblende+ plagioclase+ quartz+ garnet+ ilmenite± biotite± clinopyroxene± orthopyroxene± titanite. SPMS garnet-amphibolites possess two distinct textures. Samples collected on the ridge just to the west of Thompson Peak contain various amounts of OPX and plagioclase symplectic replacement of garnet. Analysis of samples collected by Degraff (1996) in the same location demonstrate that this symplectic reaction is the result of isothermal decompression at granulite conditions. Amphibolites from the SPMS in the rest of the range do not have rimming textures and appear to be in equilibrium with the matrix. Garnets are large (3-4 mm), subhedral to euhedral and contain some small inclusions (Figure 1). PMMMS garnet-amphibolites contain the same assemblage as SPMS amphibolites but have a distinctly different texture. Garnets are small (1-2 mm) and only slightly porphyroblastic. They are anhedral to subhedral and contain numerous large (0.3 - 0.5 mm) inclusions of hornblende, quartz and plagioclase (Figure 2).

Traverses and element maps for garnets in both units have distinctly different garnet zoning patterns (Figures 1 and 2). Large SPMS garnets (Figure 1) possess patterns typical of growth zoning while smaller SPMS garnets (Figure 4) contain similar trends but are more effected by volume diffusion (Spear, 1993; Alcock,1996). PMMMS garnets (Figure 2) have flat zoning profiles for Mg and Mn while Ca and Fe vary greatly near the core and rim. Both PMMMS and SPMS garnets have similar trends in Ca and Fe initially away from the rim, a decrease in