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.

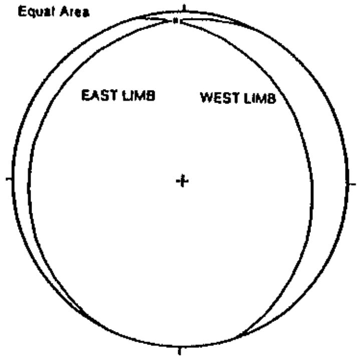
METHODS:

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).

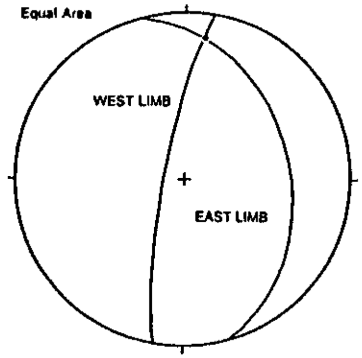
Traverses and element maps for garnets in both units have distinctly different garnet zoning patterns (Figures 1 and 2). Large SPMS garnets (Figure 1) possess patterns typical of growth zoning while smaller SPMS garnets (Figure 4) contain similar trends but are more effected by volume diffusion (Spear, 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



HORSE CREEK

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

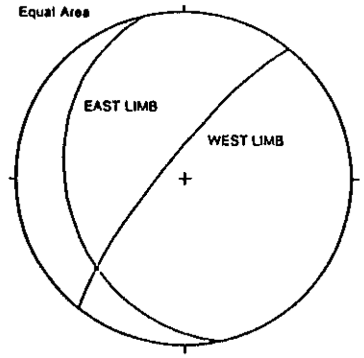
POINT OF INTERSECTION
Trend: 357 Plunge: 6 N



QUARTZ CREEK

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

POINT OF INTERSECTION
Trend: 008 Plunge: 14 N

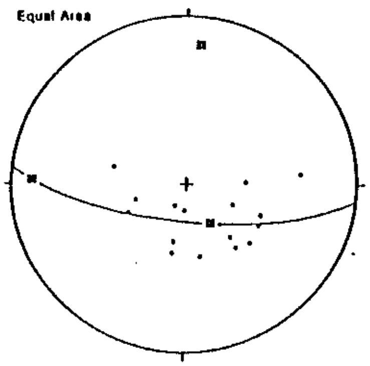


MILL CREEK

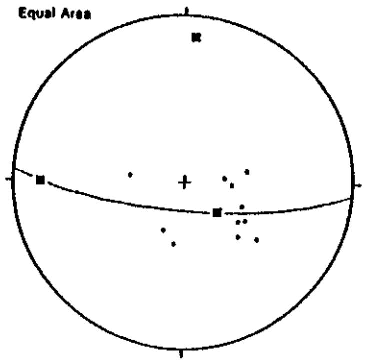
West Limb	East Limb
Strike: 039	Strike: 346
Dip: 79 W	Dip: 30W

POINT OF INTERSECTION
Trend: 224 Plunge: 26 N

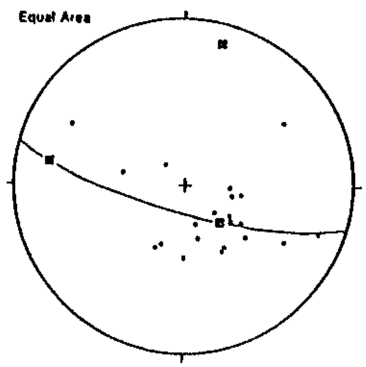
Figure 2. Lower hemisphere projection of marble fold axis orientations in the ICMS determined from total station problem analysis of the orientation of two limbs of each fold. Intersection of girdles represents fold axis.



HORSE CREEK
Trend: 005 Plunge: 10 N



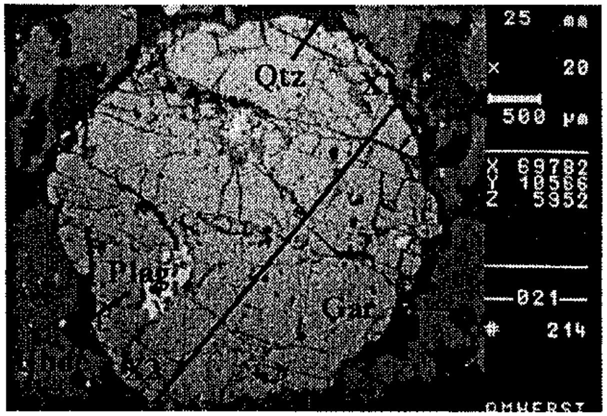
QUARTZ CREEK
Trend: 003 Plunge: 8 N

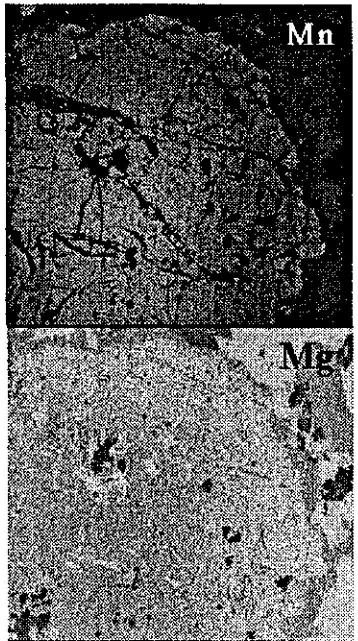


MILL CREEK
Trend: 15 Plunge: 8 N

LEGEND
- □ Represents interesection
- ○ Represents poles of foliation
- ◜ Represents best fit girdle
- ■ Represents pole

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





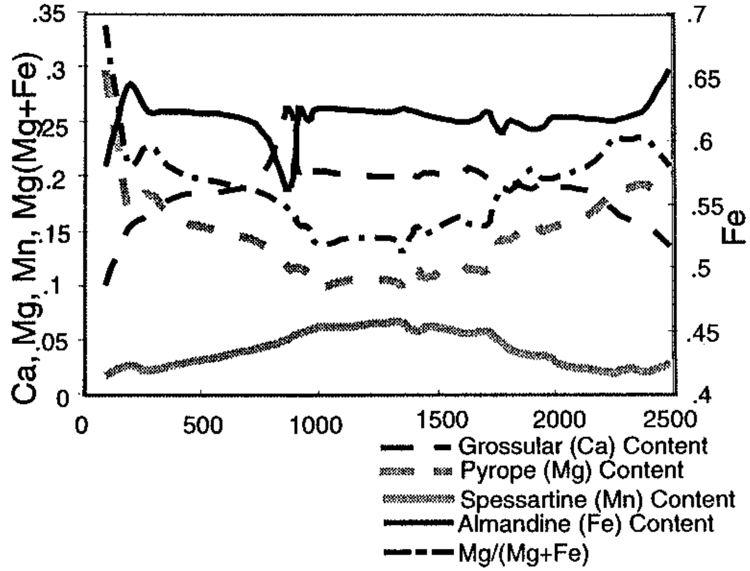


Figure 1

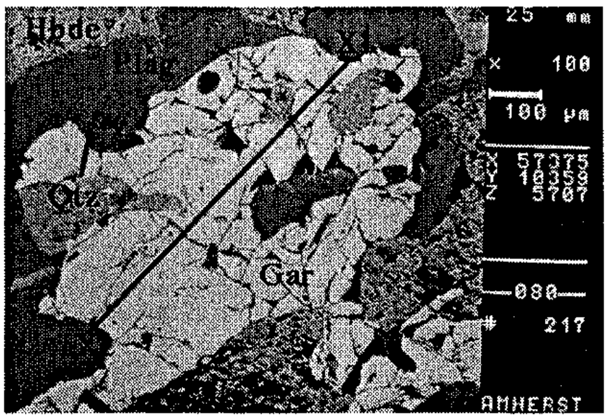
KJS18A, Lost Cabin Lake, SPMS

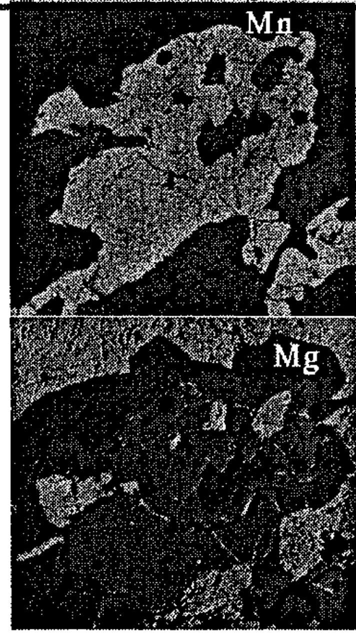
-Increasing Mn and Ca towards core
-Decreasing Mg and Fe toards core
-Preservation of growth zoning

Figure 2

KJS7A, Sunrise Lake, PMMMS

-Mg nearly unzoned, slight near rim decrese
-Slight decrease in Mn towards core
-Evidence of coalescing growth of garnet
-Diffusion zoning dominates in Mg and Fe





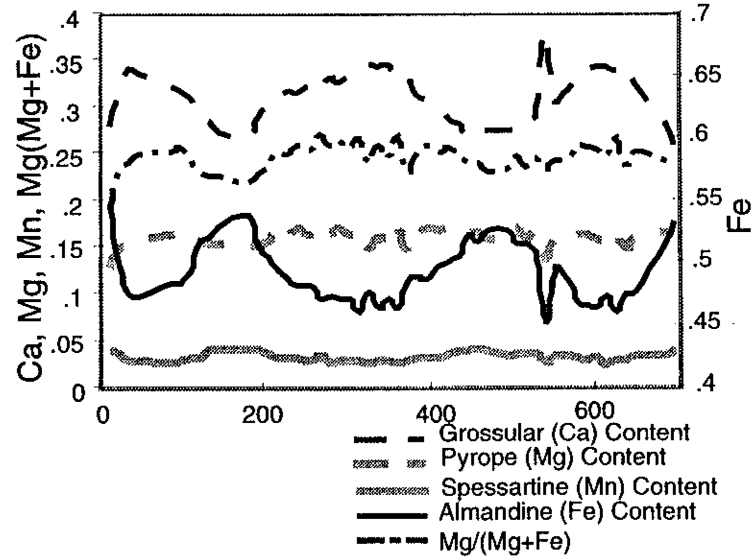
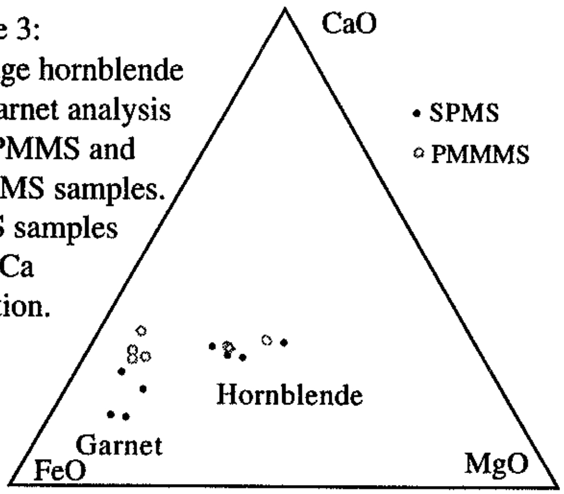


Figure 3:
Average hornblende and garnet analysis for SPMMS and PMMMS samples. SPMS samples show Ca depletion.



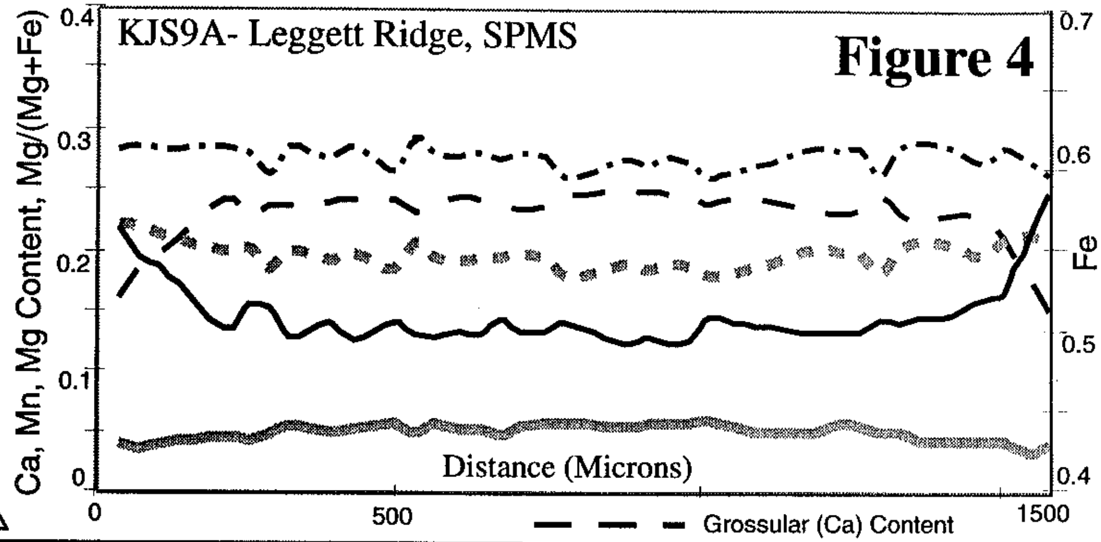


Figure 4 (above): Garnet traverse on KJS9A, Leggett Ridge, SPMS. This garnet is smaller than KJS18A(Figure 1). The garnet zoning has a much flatter profile and significant near rim effects.

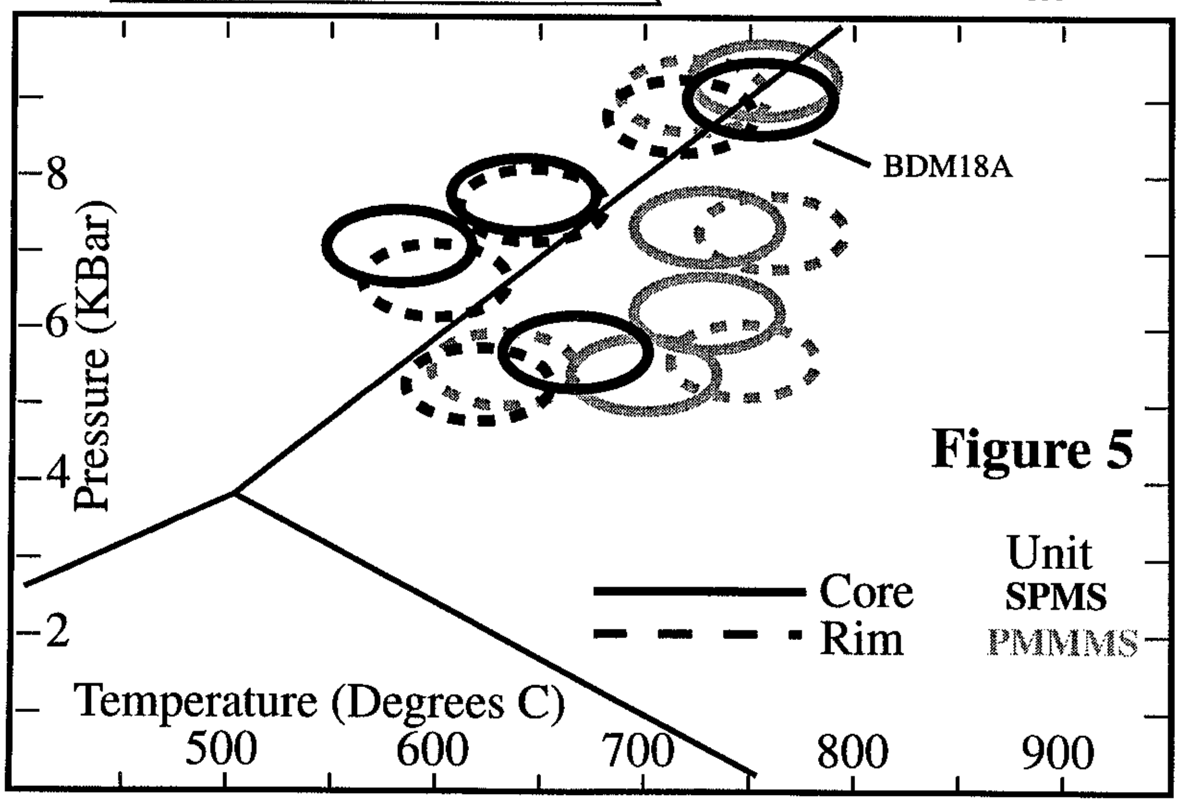


Figure 5 (at left): Geothermobarometry results. PMMMS garnet-hornblende pairs show a higher temperature calculated by Graham and Powell's(1984)thermometer. However, PMMMS garnets contain more Ca and have experienced more volume diffusion due to their smaller size and numerous inclusions. Both of these factors cause this thermometer to overestimate temperature for PMMMS samples. BDM18A is a SPMS sample with Ca similar to PMMMS samples which yields a calculated temperature similar to PMMMS samples.

Fe and increase an in Ca. SPMS garnets and hornblendes have similar Mg/(Mg+Fe) but higher Ca than their PMMMS counterparts (Figure 3). Distinct trends are apparent for calculated P-T condition for the SPMS and PMMMS (Figure 5). The PMMMS and SPMS yield similar pressures, whereas PMMMS samples yield a higher calculated temperature.

Discussion:

The most consistent explanation for the garnet zoning and GTB results is the reequilibration of SPMS and PMMMS garnet-amphibolites during the 1.7-1.8 Ga amphibolite event. Although the garnet zoning profiles for SPMS and PMMMS samples appear distinctly different they record the same event on garnets of different shape, size and composition. PMMMS garnets tend to possess flatter zoning profiles in Mg and Mn due to the increased effects of volume diffusion on zoning patternsof smaller garnets. Small SPMS garnets contain similar features (Figure 4).

Two factors cause SPMS and PMMMS garnets, which equilibrated under similar conditions, to yield consistently different temperatures. Graham and Powell's (1984) thermometer contains a correction for Ca content due to the non-ideal mixing of Ca. Ca has a much larger ionic radius than Mn and Fe and especially Mg. The presence of large amounts of Ca will limit the amount of smaller cations, especially Mg, incorporated into garnet's crystal structure. In high Ca garnets, Fe and Mn will be incorporated preferentially at the expense of Mg due to non-ideal mixing. The correction causes Ca rich samples (PMMMS) to yield higher temperatures than Ca poor samples (SPMS) given the same Mg/(Mg+Fe). BDM18A, from the SPMS, has a Ca content similar to PMMMS samples and yields a temperature similar to the trend of the PMMMS (Figure 5). Recent work (by Alcock, 1996) indicates that non-ideal mixing of Ca has decreasing effects on Mg/(Mg+Fe) with increasing metamorphic grade and volume diffusion, especially near the garnet core. Therefore, the Ca correction will tend to overestimate temperature (Alcock, 1996). The smaller, anhedral garnets of the PMMMS are much more effected by volume diffusion. Both of these factors lead to higher calculated temperatures in PMMMS samples. Simple calculations using Graham and Powell's calibration confirm that differences in Ca content and volume diffusion could lead to the variation seen in SPMS and PMMMS samples even if they equilibrated under similar conditions. There is no systematic variation in geographic location or metamorphic evolution which accounts for the variation in calculated temperature of SPMS and PMMMS samples. The pressure variation in both suites may be related to differential reequilibration during decompression on a clockwise P-T-T path.

The presence of relict garnet surrounded by symplectic OPX-plag in garnet-amphibolites from Thompson Ridge and aluminous lithologies (relict kyanite) throughout the range (Archuleta, 1994; Tierney, 1994; Monteleone, this volume) indicate that both the SPMS and ICMS/PMMMS were metamorphosed at higher P-T conditions than recorded in garnet-amphibolites. MMDS present in the ICMS/PMMMS yield GTB results similar to those in this study (Mohlman, 1996; Carmichal, this volume). However, it is possible that all evidence for earlier high P conditions in the MMDS could have been destroyed by retrograde metamorphism and hydration during the later amphibolite event. These factors are consistent with following chronology: 1) Metamorphism of the SPMS and PMMMS/ICMS at deep crustal levels during a high P, low T event; 2) Intrusion of MMDS; 3) Juxtaposition of the SPMS and ICMS/PMMMS; 4) High T, low P metamorphism recorded in garnet-amphibolites in the range.

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