Geothermobarometry of metamorphosed mafic dikes and sills, Tobacco Root Mountains, southwestern Montana

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INTRODUCTION

The Archean metamorphic rocks of the Tobacco Roots Mountains can be divided into three main lithologic units: the Indian Creek Metamorphic Suite (ICMS), the Pony-Middle Mountain Metamorphic Suite (PMMMS), and the Spuhler Peak Metamorphic Suite (SPMS). The SPMS primarily consists of metamorphosed mafic volcanic rocks of an oceanic crustal origin with minor metasediments, while the PMMMS and ICMS contain rhyolitic (Abeyta, this volume) to basaltic metaigneous rocks and metasediments. At least two generations of metamorphosed mafic dikes and sills (MMDS) cross-cut foliation in the ICMS and PMMMS but are not present in the SPMS, although they are present within one meter of it. This uneven distribution of MMDS suggests that the SPMS was juxtaposed with the ICMS and PMMMS after the intrusion of the MMDS.

All units exhibit upper amphibolite to lower granulite grade metamorphism, but several metamorphic events have affected the area. Although the MMDS cross-cut foliation and folds in the ICMS and PMMMS, many of these MMDS are folded themselves. Therefore, at least one metamorphic event must have occured after their intrusion. Owen (1996) has determined that the contact between the SPMS and the ICMS/PMMMS is folded as well, and that the orientation of this contact fold is concordant with the orientations of folds in the MMDS and folds in the ICMS and PMMMS. The similarities of these fold orientations indicates that they were folded together during a period of metamorphism, possibly at around 1.8 Ga (Brady et al., 1994). This study was undertaken in the hope that the pressures and temperatures recorded in the MMDS in the Tobacco Root Mountains would clarify the metamorphic history of the area, and the tectonic processes that affected it.

FIELD OBSERVATIONS

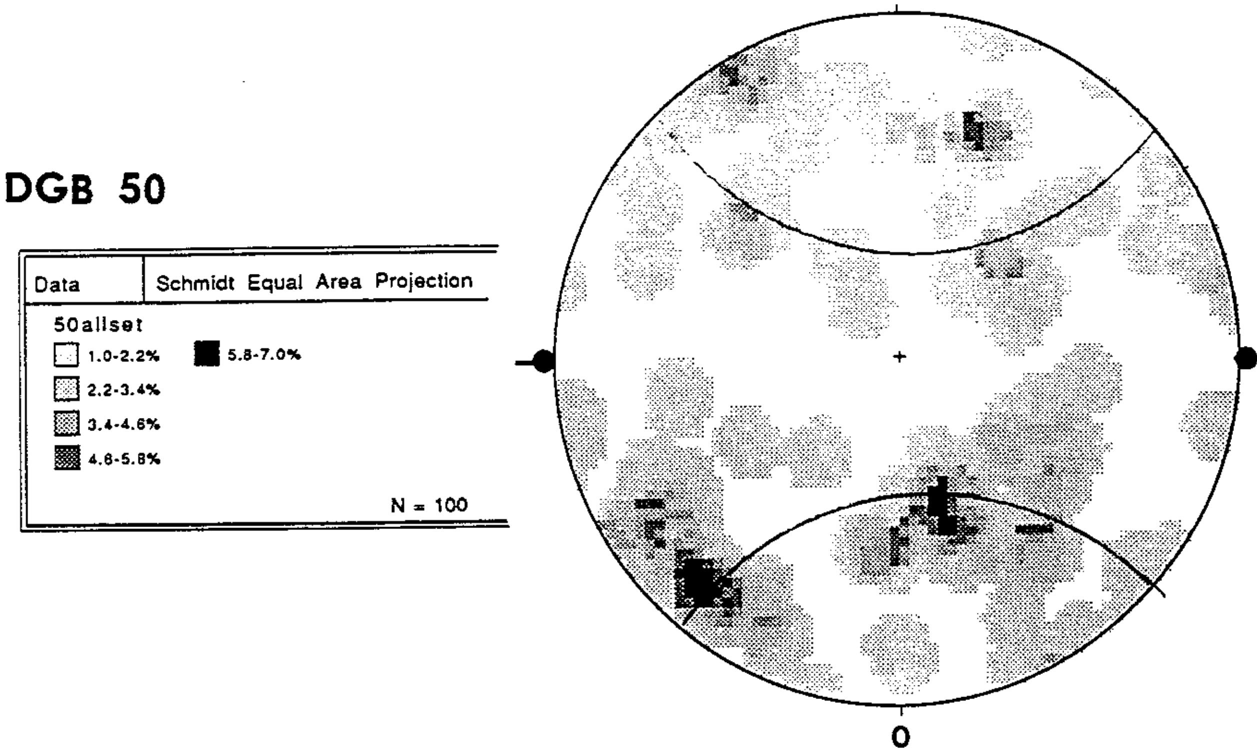
Sixty-six samples of MMDS were collected from a variety of locations across the ICMS and the PMMMS. The MMDS were identified by their gray to black color on fresh surfaces, blocky and brown weathering pattern, fine grain size (0.5 to 2 mm), and cross-cutting relationships with surrounding rock units. Since the hornblende gneiss present in the ICMS and PMMMS generally looked similar to MMDS, cross-cutting relationships with the country rock were the primary criteria used to distinguish between these two rock types.

Samples displayed a variety of visible textures, most noteably a decrease in grain size from the centers of the dikes to the margins of the dikes. In many MMDS there was also a change in mineralogy as well, with biotite and/or amphibole abundant on the margins of the dikes and with garnet and clinopyroxene more prominent in the centers. The abundance of amphibole on the margins of the dikes can be explained by the limited availability of water during metamorphism. Vitaliano et al. (1979) describe MMDS as having sharp contacts against the country rock, with chill margins that indicate emplacement into cool rocks during or after an earlier metamorphic event. Since MMDS do not have igneous mineral assemblages, finer grain sizes on the margins of the MMDS cannot accurately be called chill margins, although they might have been influenced by relict igneous textures.

Foliation in MMDS is parallel to the dike walls rather than to the foliation of the country rock, although many MMDS have a foliation that is nearly concordant to the foliation of the country rock. In some areas, such as Sunrise Basin and the Nicholson Mine region, younger MMDS cross-cut older MMDS. Generally, the younger MMDS have finer grain sizes, while the older MMDS have a somewhat coarser texture with more compositional banding. In many cases, both sets of MMDS have garnets; therefore, they both underwent some sort of metamorphism after the younger dike was emplaced.

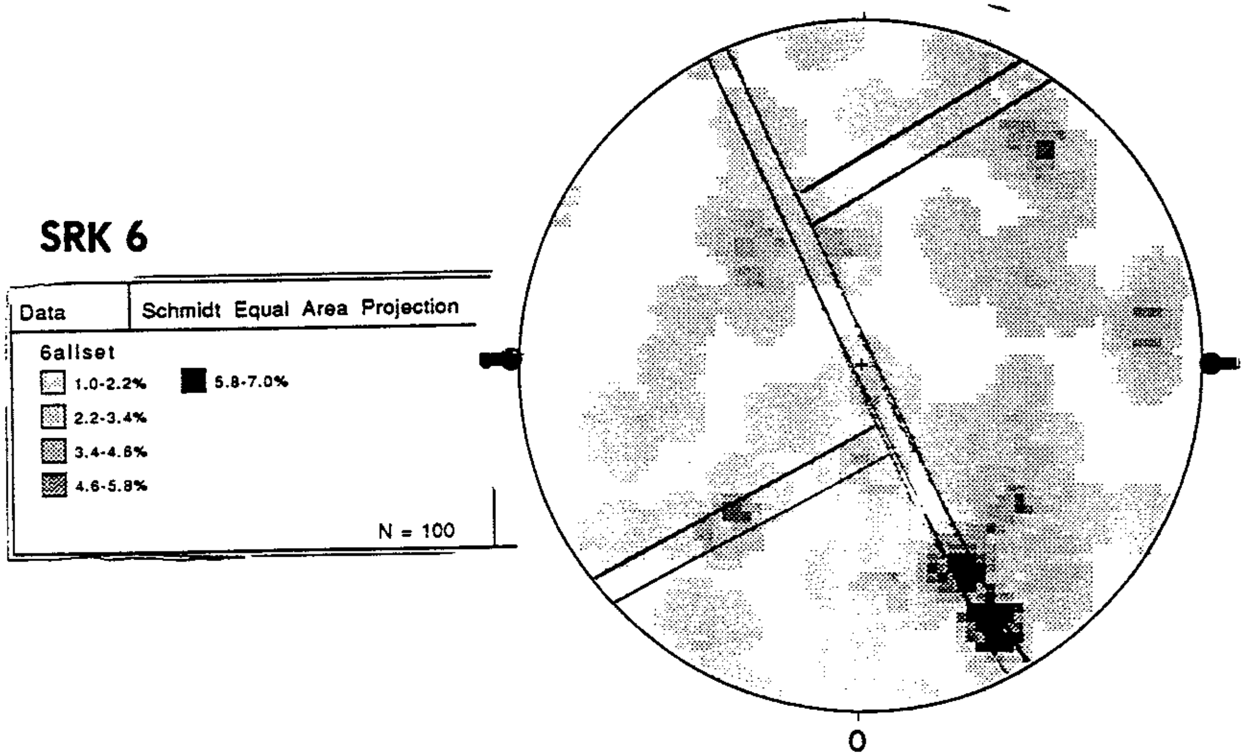
PETROGRAPHY

MMDS commonly contain garnet, hornblende, clinopyroxene, plagioclase, quartz, ilmenite, and biotite. The relative amounts of these minerals vary between separate dikes and also across the margins and interiors of individual dikes. Generally, the margins of each dike or sill are richer in hornblende and biotite and depleted in garnet



Sample **DGB50** is a quartzofeldspathic gneiss from the ICMS at Thompson Ridge. The plot of quartz C-axis data is difficult to interpret in terms of penetrative simple shear. It may indicate pure shear flattening; a preliminary interpretation is shown. Lineation is parallel to the E/W axis.

Sample **SRK6** is a quartzofeldspathic gneiss from the ICMS at Mustard Pass. It is possible to make a preliminary interpretation of simple shear based on the presence of a weak crossed girdle pattern in the quartz C-axis data plot. Lineation is parallel to the E/W axis.



and clinopyroxene, while the interiors contain more evenly distributed amounts of these minerals. According to Hanley and Vitaliano (1983), hornblende makes up 40 to 60% of margin compositions, while clinopyroxene and garnet each account for less than 10%. The non-margin samples are characterized by 10 to 30% each of hornblende, clinopyroxene, and garnet.

Three major textures were determined for 66 thin sections of MMDS: granoblastic, clustered granoblastic, and laminated. The granoblastic samples had even distributions of equigranular minerals throughout the slide, while the clustered granoblastic variety exhibited large groups of plagioclase and hornblende surrounding "islands" of garnet+clinopyroxene aggregates. The slides with laminated textures commonly exhibited some clustered granoblastic features, but the preferred orientation of the hornblende or biotite caused the clusters to form streaks or lenses instead of blobs. Strands of ilmenite were also indicative of laminated textures; in the clustered granoblastic variety the ilmenite orientations were much more random.

The textural variations between minerals in the MMDS were pronounced. Garnets had reacted with surrounding minerals to such a degree that the crystal forms were subhedral at best. Up to 80% of the garnets contained inclusions of quartz, hornblende, clinopyroxene, ilmenite, and rarely, plagioclase, while only 20% did not contain inclusions. Most of the garnets appeared to be broken, as if they had been smashed or chewed up, or eaten away and dissolved into an "oil and water" texture (Figure 1). Larger garnets occurred as garnet+clinopyroxene clusters, and always contained inclusions. Hanley and Vitaliano (1983) noted that garnets also appeared as incomplete coronas separating "relict" plagioclase clusters from clinopyroxene.

Clinopyroxene is an interesting mineral in the MMDS; it has two distinct habits, described by Hanley and Vitaliano as "metamorphic" and "relict." The common "metamorphic" clinopyroxenes occur as small, anhedral grains with few inclusions, and are typically in proximity to garnet. "Relict" clinopyroxenes are generally not as common, have a subhedral to euhedral form, contain bands which appear to be exsolution lamellae, and may be up to four times larger than their metamorphic counterparts. SEM analysis indicates that these "relict" clinopyroxenes are probably not igneous relicts since they contain inclusions of hornblende.

Orthopyroxene was found in samples from the Quartz Creek region of the ICMS, in equigranular (< 0.2 mm) clusters with clinopyroxene. The presence of orthopyroxene in rocks with metabasalt assemblages indicates a higher grade of metamorphism (lower granulite rather than upper amphibolite). Orthopyroxene was not observed in any MMDS samples from the PMMMS.

Clusters of equigranular plagioclase are present in most samples of MMDS, although most of the interiors of these clusters have been altered to fine-grained minerals such as sericite. Chemical zoning (higher An rims) within individual crystals can be observed petrographically, although the zoning is not consistent. Hornblende may also form clusters, although the grain size among the hornblende crystals is less uniform. Hornblende is commonly the mineral which defines the texture in each of the MMDS; the hornblende habit determines if the sample is granoblastic, clustered granoblastic, or laminated. Large ilmenite blobs are present only in these hornblende clusters; ilmenite appears only as specks in other portions of the slide, especially around clinopyroxene.

CHEMICAL ANALYSIS

Nine samples of MMDS were chemically analyzed using a Zeiss Digital Scanning Electron Microscope with a LINK Energy Dispersive Spectrometer, as well as with a Cameca SX50 Microprobe at the University of Massachusettes. Individual mineral compositions were obtained for eight of the slides, and four of the slides were mapped for elemental distribution of Al, Ca, Fe, and Mg. Garnet compositions, analyzed on the rims and cores of each crystal, show no zoning in Mn, Ca, Mg, or Fe, and according to the X-ray chemical maps are not zoned in Al, either. The grossular, spessartine, almandine, and pyrope components range from $Gr_{18}Sp_{1.5}Al_{59}Py_{20}$ to $Gr_{21}Sp_2Al_{66}Py_{11}$ across the region, but do not exhibit much variation in individual samples.

Neither hornblende nor clinopyroxene generally show much chemical zoning in the chemical maps or in the point analyses. There is one important exception to this, however, in the sample SKC-97-2-2a from the Quartz Creek area in the ICMS. The presence of orthopyroxene in this sample indicates granulite phase rather than upper amphibolite phase metamorphic conditions, and the clinopyroxene crystals in this sample show distinct Al-rich cores, indicating decompression in the P-T history. Mg/(Mg+Fe) ratios for clinopyroxene range from 55% to 72% across the region, and range from 39% to 62% for hornblende. These analyses, as well as the garnet analyses, are consistent with those obtained by Mohlman (1996) in her work on MMDS.

Regional plagioclase rim compositions range from An_{28} to An_{49}, with core compositions ranging from An_{25} to An_{43}. The higher Ca content in the rims can also be seen in the distribution maps, indicating reverse zoning due to pressure and temperature increases as the crystal grew. This zoning is preserved in the plagioclase even after decompression due to the slow diffusion rate of the coupled substituents Ca+Al and Si+Na. The presence of zoning in the plagioclase, and absence of significant zoning in the other minerals used in the geothermobarometry calculations (garnet and hornblende) means that core to core and rim to rim comparisons between these minerals cannot be made due to the differences in chemical diffusion rates. For this reason, only near-rim compositions were used to determine the pressures and temperatures experienced by the MMDS.

GEOTHERMOBAROMETRY

Pressures and temperatures for the metamorphism of the MMDS (Figure 2) were calculated using Kohn and Spear's 1996 program Thermobarometry 2.0, with the Graham and Powell (1984) garnet-hornblende thermometer and the Kohn and Spear (1990) garnet-hornblende-plagioclase-quartz (tschermakite-Mg) barometer. It is interesting to note that the highest calculated pressures and temperatures (8.5-10 kb and 650-700°C) are found in the samples near the nose of the folded SPMS and ICMS/PMMMS contact at Sunrise Basin (1-3a) and Noble Lake (3-4). Sample 1-3b, a younger cross-cutting dike from Sunrise Basin, reveals some puzzling information. Its pressures and temperatures (7.5 kb and 600-650°C) are much lower than the MMD that it cross-cuts (1-3a), indicating very different peak metamorphic conditions. For the sample locations further and further away from the folded contact between the three units, calculated pressures and temperatures are lower and lower. In the ICMS, conditions drop slightly to 8.5 kb and 650°C in the Sunbeam Mine area (12-3), and to 8 kb and 650-700°C in the Horse Creek area (11-2). The ICMS also contains the orthopyroxene-bearing sample from Quartz Creek (2-2a), which indicates temperatures between 800 and 900°C and pressures ranging up to 12 kb. In the PMMMS, temperatures and pressures drop to 8 kb and 650°C at Cataract Mountain (KJS-34A), and decrease further to 6.5 kb and 625°C in Antelope Creek (8-3).

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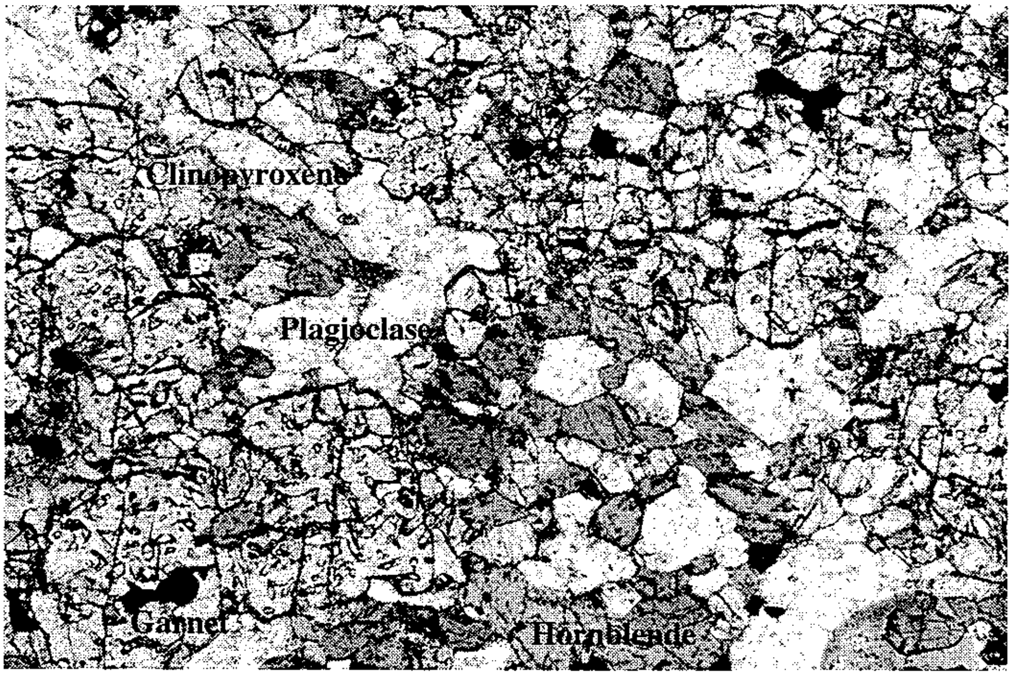

Figure 1. Typical clustered granoblastic MMD with abundant garnet inclusions, from Cataract Mountain (PMMMS).

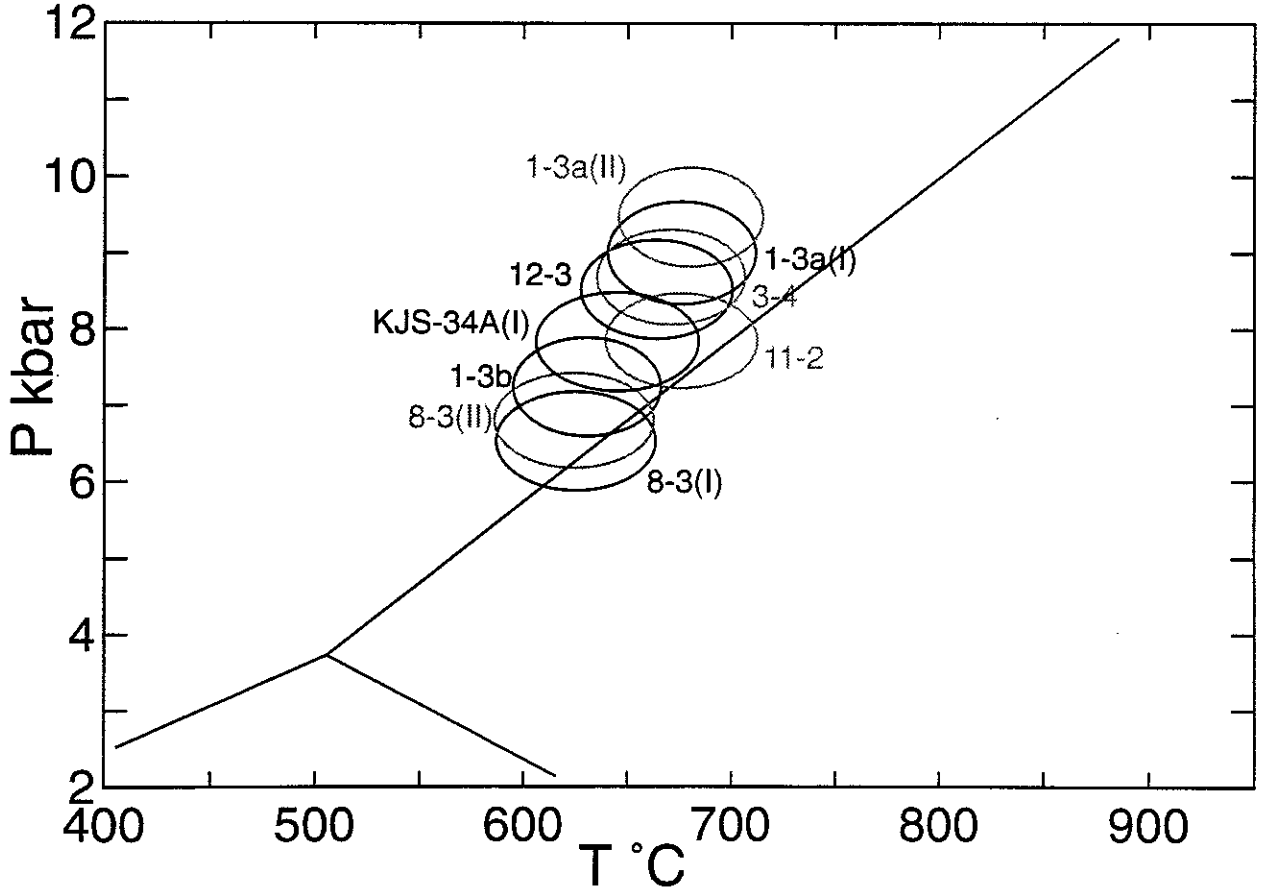

Figure 2. Pressure-temperature graph of samples from around the ICMS and PMMMS. Geothermobarometry results were calculated from near-rim compositions of garnet, hornblende, and plagioclase.

Geothermobarometry of Garnet Amphibolites from the Indian Creek and Pony-Middle Mountain Metamorphic Suites, Tobacco Root Mountains, Montana

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INTRODUCTION

The Tobacco Root Mountains (TRM) (fig. 1) contain three Archean metamorphic suites: the Indian Creek (ICMS), Pony-Middle Mountain (PMMMS), and Spuhler Peak (SPMS) (Burger et al, 1996). The ICMS and PMMMS have very similar compositions and rock types. The ICMS is composed of quartzofeldspathic gneisses, pelitic schist, marble, quartzite, and iron formation. The PMMMS is dominated by quartzofeldspathic gneisses with lesser amounts of hornblende-plagioclase gneiss and amphibolite, but has only minor amounts of marble and quartzite. Both the ICMS and PMMMS are primarily composed of metaigneous rocks. Geochemical analysis of quartzofeldspathic gneisses and structural observations in the ICMS and PMMMS suggest that the two suites may be of single parentage (Burger et al. 1996).

Whole rock Rb/Sr and U/Pb zircon analysis of high grade basement rocks in the TRM give Archean to Proterozoic ages of ~3.3, 2.7, and 2.4 Ga (Krogh et al., 1997). Two significant metamorphic events have been documented in the rocks of the TRM. Geothermobarometry for metamorphosed mafic dikes and sills (MMDS) in ICMS and PMMMS, and amphibolites in SPMS is consistent with a clockwise P-T path with initial prograde metamorphism at >10 Kb due to a collisional event, followed by a ~5.5 Kb metamorphism due to decompression. Thus the ICMS, PMMMS, and SPMS must have been assembled before the Archean (Cheney, 1996). The last major metamorphism occurred at 1.8 Ga, at temperatures greater than 500°C, from $^{40}Ar/^{39}Ar$ ages from hornblende-amphibolites of the SPMS, ICMS, and MMDS in the ICMS (Kovaric et al, 1996).

Little detailed petrology is available for the ICMS and PMMMS. Mineral assemblages for both suites are generally consistent with those of the SPMS, but there is no data on the variation of P & T over the whole range. The ICMS and PMMMS make up most of the Archean rocks in the area. Both units contain Quartz-Garnet-Plagioclase Amphibolites that can be used to evaluate the differences in P & T within each suite as well as the systematic variation in P's & T's across the TRM. Detailed study of these amphibolites also provides a direct comparison to the well characterized amphibolites in the SPMS.

METHODS

About sixty garnet-amphibolites were collected throughout the ICMS and PMMMS. Of the sixty samples collected, thirty-five were cut into thin-sections and described for mineralogy and texture. Of those thirty-five thin-sections, six representative samples, three from the ICMS and three from the PMMMS representing a wide geographical distribution, were chosen for analysis using a Zeiss DSM 960 with a Link EDS Scanning Electron Microscope. Point analyses and garnet traverses were done in one or two areas of each slide

Representative analyses of both mineral rims and interiors were used in the program "Thermobarometry 2.0" (Kohn and Spear, 1997) to determine P's & T's of metamorphism. Graham and Powell's (1984) garnet-hornblende and Patiño-Douce et al.'s (1993) garnet-biotite models were used for geothermometers. Kohn and Spear's (1990) garnet-plagioclase-hornblende (Mg-tschermak)-quartz model was used as a geobarometer. No Fe^{3+} corrections were made.