The Mineralogy and Petrology of Garnet-Amphibole Rocks from the Spuhler Peak Formation along Thompson Peak Ridge, Tobacco Root Mountains, SW Montana

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INTRODUCTION

A nearly continuous sequence of the Spuhler Peak Formation (SPF) is exposed along Thompson Peak Ridge, in the Noble Creek Quadrangle of SW Montana. This study focuses on the garnet-amphibole rocks along Thompson Peak Ridge. The purpose is twofold: Firstly, to study the mineralogy and petrology of the garnet-amphibole rocks. Secondly, to obtain pressures and temperatures that affected the rocks. The spectacular mineral assemblages in these rocks provide valuable information about the metamorphic history of the SPF in this area. The SPF is of interest as it may represent Archean oceanic crust that has been subsequently thrust over supracrustal basement.

METHODS

A stratigraphic section of the rocks exposed along Thompson Peak Ridge was jointly created with Kara Tierney (Amherst College). Approximately seventy samples were collected and, of these, twenty-eight thin sections were made. Five sections were examined using a scanning electron microscope (SEM). Chemical analyses were determined using the energy dispersive spectrometer on the SEM. These chemical analyses were used to calculate temperatures using the Hodges and Spear (1982) garnet-biotite geothermometer. Pressures were estimated by plotting mineral assemblages on a petrogenetic grid for cordierite-anthophyllite rocks based on experimental data in the AFM subsystem (Spear, 1993).

RESULTS AND DISCUSSION

Petrography and Mineral Chemistry

The garnet-amphibole rocks along Thompson Peak Ridge range from coarse grained gneisses to garnetite. Hand samples are characterized by coarse blades of luminescent gedrite, coarse aggregates of biotite, garnets (up to 10cm in diameter) and coarse quartz grains. Cordierite, cummingtonite, kyanite, sillimanite, hornblende, and even corundum are not as obvious in hand sample, but are nevertheless important to this study.

The most common rock in this study is characterized by the mineral assemblages: quartz+plagioclase+garnet+cummingtonite+biotite or quartz+plagioclase+garnet+orthoamphibole+biotite. All but one of the thin sections have coarse grains with equilibrium textures. Most of the minerals are subidioblastic (with at least two distinct crystal faces) and approximately 35% of the garnets are poikioblastic porphyroblasts with inclusions of biotite, quartz, plagioclase, chlorite, and minor amounts of amphibole. Amphiboles, plagioclase, and garnets have "broken" or "chewed up" textures.

Geothermometry

Temperatures were calculated using zoned garnets and homogeneous biotites from *sample LA-10B*. A temperature estimate of 750 °C was obtained from the compositions of average garnet rims and average biotite.

Caution should be exercised in using calculated temperatures as it is likely that the biotite has changed its composition even though analyses show no zoning. In calculating the temperatures, the average rim compositions of the garnets were used because the core compositions are out of equilibrium with the biotite and the extreme rim (the outermost edge of the crystal) most likely reflects a change in composition due to cooling. The average rims and biotite groundmass compositions provide the most reliable estimate for temperature of metamorphism.

Aluminous Reaction Coronas

Of particular interest, due to its unique textures and compositions, is a kyanite-corona rock (*sample LA-32*). As shown in Figure 1, the isolated inclusions surrounded by coronas are microscopic (2 mm), typically elongate, and typically cored by kyanite. The kyanite is surrounded by thin reaction coronas of almost pure anorthite and vermicular spinel. The spinel-anorthite zone is in turn armored by rinds of cordierite which are surrounded by gedrite and a low Al amphibole.

In addition to the coronas, there is one fragmented garnet in the thin section. Four individual pieces of this garnet are enclosed by a moat of plagioclase with small cordierite inclusions. Each garnet section is concentrically zoned indicating that the zoning took place after the deformation of the garnet. Garnet rims are higher in magnesium and manganese than the cores, while iron content remains relatively constant. The rest of the garnet is fractured and occurs within a matrix of cordierite+plagioclase+orthoamphibole.

Corundum occurs as a minor component of *sample LA-32* and is only identifiable microscopically. SEM photos magnified ≥500X show subidioblastic grains of corundum in contact with the anorthite-spinel rims.

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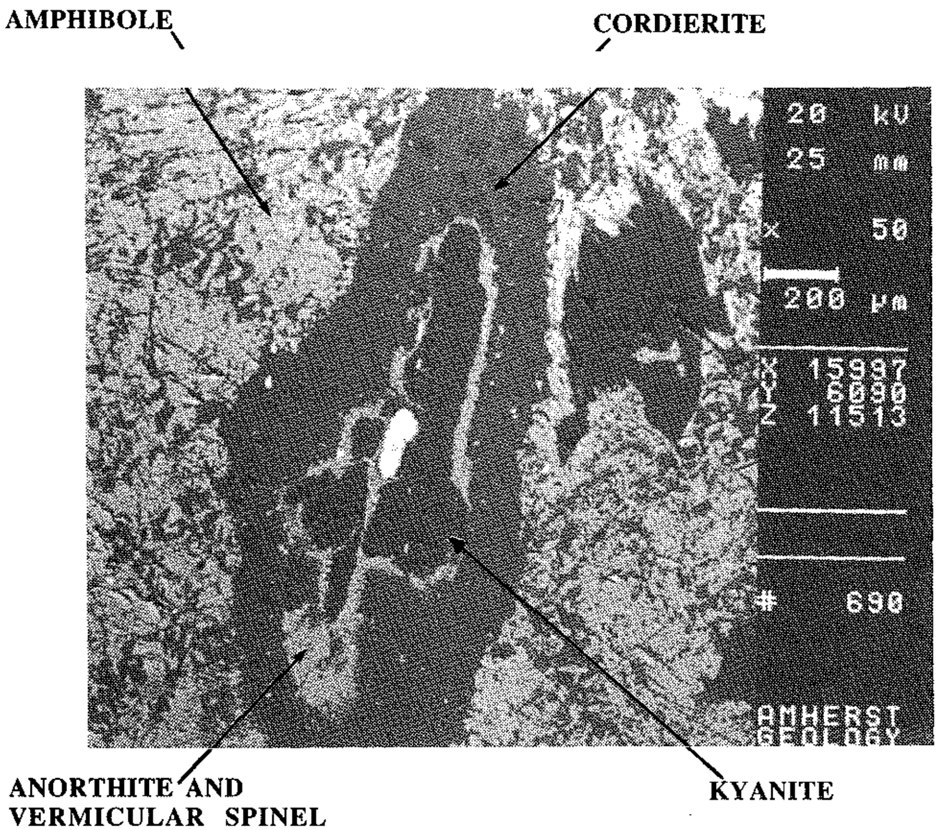

FIGURE 1. SEM photo showing kyanite enclosed in anorthite-spinel coronas.

Phase Relations

Spear and others have created diagrams from metamorphic assemblages that can be used to constrain the pressures and temperatures of rocks in the field. These diagrams are referred to as petrogenetic grids. Spear's (1993) P-T diagram shows an empirical petrogenetic grid for cordierite-anthophyllite rocks and provides an important tool for understanding and illustrating the development of the aluminous reaction coronas in *sample LA-32.* (Fig. 2).

A portion of this petrogenetic grid shows two phase diagrams that represent the reaction(s) that produced both the non-corona and corona rocks (Fig. 2, pts. A and B). On each of these diagrams the assemblage garnet+orthoamphibole+cummingtonite (± hornblende) can be plotted. This assemblage occurs in both rock types and consequently does not reveal much about the history of these rocks. However, the occurrence of kyanite in the rock that also contains garnet+cordierite suggests a decompression event. The occurrence of kyanite in orthoamphibole rocks requires pressures >10 kb.

The presence of cordierite and aluminosilicates partially constrains the pressure and temperature history of the rocks. Schumacher and Robinson (1987) have shown that in rocks with compositions similar to those in this study, reactions involving cordierite are strongly pressure dependent. I suggest that the reactions that take place to form the corona rock in this study are also pressure dependent. The phase diagrams representing the two different assemblages thus indicate a decrease in pressure that does not necessarily change the temperature. The occurrence of undeformed coronas enclosing kyanite is consistent with their development following decompression as described by Schumacher and Robinson (1987). This pressure decrease may be due to uplift or rapid erosion. However, another possibility is a second stage of metamorphism.

Geobarometry

The first evidence of decompression is revealed by the presence of sillimanite. At the temperature considered here (750 °C), sillimanite and the possibility of coexisting sillimanite and orthoamphibole indicate low pressures. Sillimanite is stable only at pressures below 10 kb and coexisting sillimanite and orthoamphibole are stable only at pressures slightly above 5 kb to 10 kb (Fig. 2). Decompression also explains coexisting garnet and cordierite which is only stable at pressures below 4 to 5 kb (Fig. 2).

The pressure at which these rocks formed depends on the cordierite. A garnet-cordierite-aluminosilicate-quartz geobarometer was not used to calculate pressures for these rocks due to the presence of water in cordierite.

Cordierite has a variable water content that depends on the "humidity" of the rocks during metamorphism and possibly on the P-T-t paths followed by the cordierite. According to Thompson (1976) and assuming a dry cordierite, the rocks in this study (garnet rims X_{Mg}=0.20; cordierite X_{Mg}=0.72) give pressures of about 6 kb and temperatures around 625 °C with an estimated uncertainty of ±2 kb and ±100 °C. These conditions are very close to the kyanite-sillimanite equilibrium curve.

Implications of coexisting orthoamphiboles

In this study, coexisting anthophyllite and gedrite have not been observed in the same rock. There are two amphiboles in some of the thin sections but it is unclear if they are both orthoamphiboles. Amphiboles with high Al (≥10%) are most likely gedrite. Fine grained, complexly intergrown amphiboles with varying Al contents may represent lower temperature anthophyllite and/or cummingtonite. The explanation for these fine grained intergrowths of amphiboles is yet to be resolved. Calculated temperatures are above the orthoamphibole solvus and thus are consistent with the observation of only one orthoamphibole in these rocks. If two coexisting orthoamphiboles occur, then the temperatures would be less than 525 °C to 575 °C, as shown on Figure 2, pt C. Of course, anthophyllite and gedrite may coexist if one is an exsolution lamellae in the other.

Reactions

According to Schumacher and Robinson (1987), in rocks composed of gedrite+sillimanite+quartz+spinel+plagioclase enclaves of aluminous minerals surrounded by cordierite developed as a result of overstepping continuous Fe-Mg reactions. They suggest in turn that this overstepping produced the cordierite and aluminous minerals. In the rocks, gedrite+sillimanite+quartz reacted to form cordierite, and quartz was consumed. Gedrite and sillimanite continued to react via several mechanisms. Most germane to this study are:

Gedrite+Aluminosilicate+H_2O = Cordierite+Corundum (1)

Hornblende may be responsible for the Ca-rich minerals (anorthite) in the kyanite reaction zones. Schumacher and Robinson (1987) propose that in rocks with hornblende, the hornblende and aluminosilicates react as follows:

Hornblende+Aluminosilicate+Quartz+H_2O = Cordierite+Plagioclase (2)

Hornblende+Aluminosilicate+H_2O = Cordierite+Corundum+Plagioclase (3)

According to Harris (1981), the phases cordierite-garnet-sillimanite-spinel are related by the reaction:

Garnet+Sillimanite = Cordierite+Spinel (4)

He also suggests that the phases corundum-cordierite-sillimanite-spinel are related by the reaction:

Spinel+Sillimanite = Cordierite+Corundum (5)

For those assemblages containing spinel, Harris (1981) suggests temperatures of 740 °C ± 20 °C and pressures of 4.8 kb ± 0.5 kb. These results are consistent with my data.

CONCLUSIONS

1. Temperatures of 750 °C were calculated for the non-corona rocks and the corona rock using average garnet rims and homogeneous biotites from *sample LA-10B*.

2. Pressures were estimated based on mineral assemblages containing garnet±cordierite +gedrite+cummingtonite±chlorite±sillimanite±kyanite. Rocks that originally contained stable kyanite formed at pressures 10 to 16 kb while the aluminous reaction rim assemblages formed at pressures ≤5 kb.

3. The sequence of events dictated by the textures in *sample LA-32* may be commensurate with two stages of metamorphism. However, this conclusion has not yet been fully developed and requires further research.

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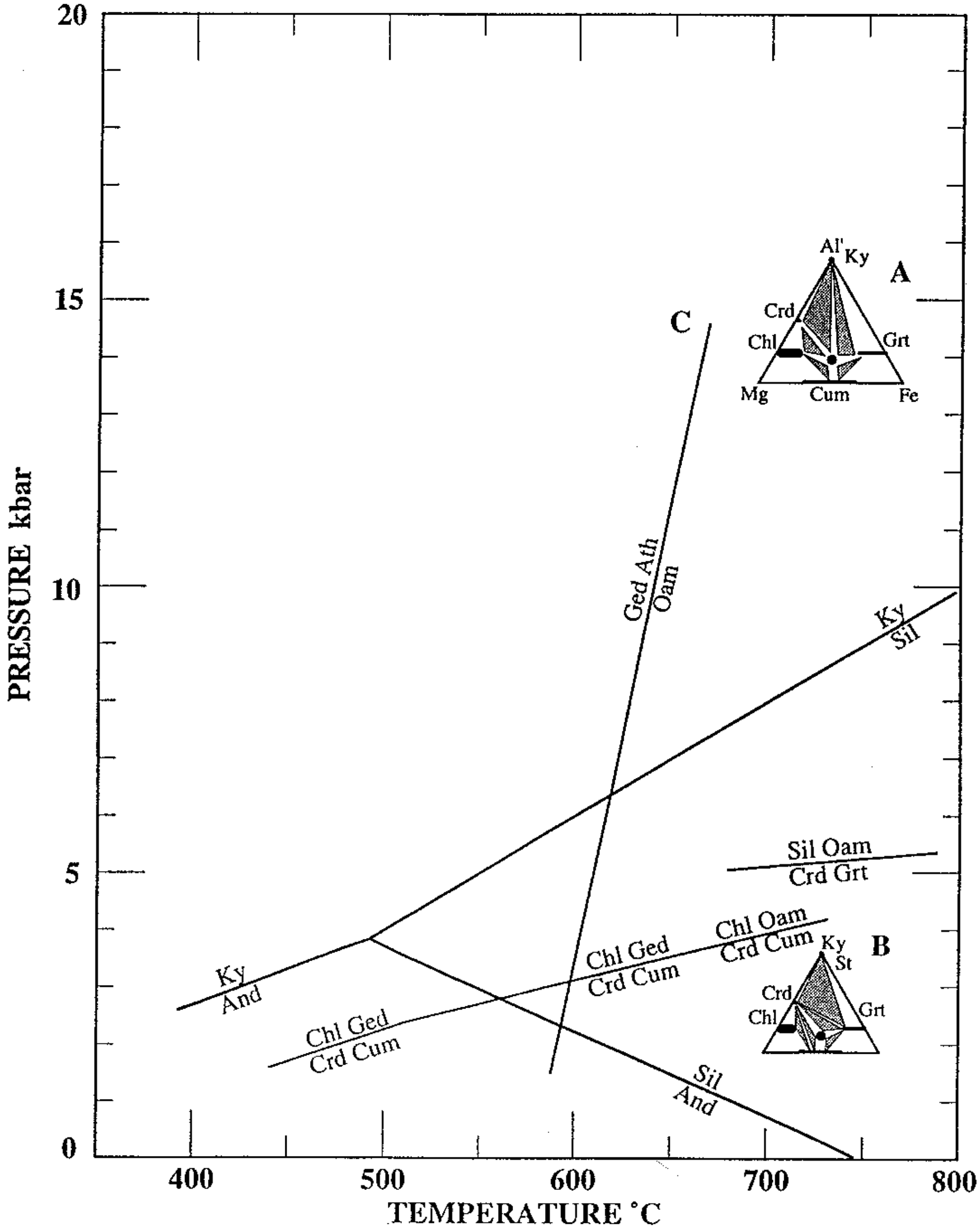

Figure 2. P-T diagram showing an empirical petrogenetic grid for cordierite anthophyllite rocks (After Spear, 1993).

Petrographic Analysis of Amphibolites from the Spuhler Peak Formation, Indian Creek Metamorphic Suite, and Pony-Middle Mountain Metamorphic Complex Tobacco Root Mountains, Montana

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Introduction:

In this project, I am looking for any petrographic and petrochemical distinctions that exist between the amphibolites from the Spuhler Peak Formation and those in the surrounding rocks of the Indian Creek Metamorphic Suite and the Pony-Middle Mountain Metamorphic Complex. The similarities and differences will further an understanding of the protoliths and metamorphic histories of the rocks in this study.

Many authors (Cummings and McCulloch, 1992; Mogk and Henry, 1988; and Wilson, 1981), who have worked in this area previously, support the theory that the Spuhler Peak Formation is a slice of oceanic crust which is now sandwiched between two formations of metamorphosed sedimentary and intruded rocks. The Spuhler Peak amphibolites are thought to have originated as submarine thoeliitic basalt flows. Amphibolites in the Indian Creek Metamorphic Suite and the Pony-Middle Mountain Metamorphic Complex are mostly from flows and sills on the margins rimming this small, rift-bounded basin (Mogk and Henry, 1988).

I am also comparing my conclusions with these models. If they do not agree, I hope to delineate reasons, such as metasomatism, that explain the discrepancies.

Field Methodology:

Samples were collected from three basic regions in the southern Tobacco Root Mountains. These locations were based mostly on accessibility of the terrain by road and foot. The northernmost area, around Noble Lake, extended from the north side of Spuhler Peak south to Mustard Pass. Samples collected here and discussed below include PC-32, 36, 42, and 77. The central collection region ran along Indian Ridge, east to Thompson Peak. Samples PC-2, 7, 15, 20, 22, 26, and 27 are from this area. Samples were also taken from a zone enclosing Leggat Mountain's west-trending ridge, Gneiss Lake cirque, and the area to the west of Lower Brahnam Lake. Samples collected in the third locality are PC-62, 63, 67, 68, and 70. Additionally, four samples were collected north of these three main regions, in an isolated pocket of the Spuhler Peak Formation. One of these samples, PC-54, is discussed below. PC-75, was collected from south of Leggat Mountain, near the road leading to Brahnam Lakes.

Two basic types of amphibolites were identified, based on appearances in the field, within the Spuhler Peak Formation (SPF). These included the more common "salt and pepper amphibolite" and the "wispy amphibolite". The first type has a salt and pepper-like appearance from the distribution of small white plagioclase and quartz crystals and of darker hornblende crystals and other mafic minerals. The second type of amphibolite has "wispy" leucosomes of felsic material. The majority of samples collected were salt and pepper amphibolites. The wispy amphibolites were less widespread, and the possible focus of another student's research.

Amphibolites in the Indian Creek Metamorphic Suite (ICMS) and the Pony-Middle Mountain Metamorphic Complex (PMMMC) did not show wisps. The amphiboltes of these two formations may be of similar composition, though the PMMMC, overall, lacks the marbles and iron formations found in the ICMS. Wilson (1981), tested the whole rock chemistry of eight amphibolite samples. Five of these amphibolites were from the Tobacco Root Mountains, in the ICMS, and three from the Ruby Range. He found that they all had identical bulk chemistries. He also stated that they compared well with other amphibolites from nearby, such as the Beartooth, Spanish Peaks, and Madison Ranges.

Discussion:

Eighteen samples from the Spuhler Peak Formation, Indian Creek Metamorphic Suite, and the Pony-Middle Mountain Metamorphic Complex were selected based on the degree to which they represented their formation's amphibolites, the amount of weathering, and a size large enough for whole rock chemical analysis. Observation through the petrographic microscope of these samples has yielded the accompanying data.

The Spuhler Peak amphibolites are the largest grained and are mainly subhedral to euhedral. The ICMS rock grains are fine to medium sized and subhedral to anhedral. PMMMC amphibolites show medium to coarse