ARCHEAN ROCKS OF THE TOBACCO ROOT MOUNTAINS, MONTANA

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Geologic Setting

The Tobacco Root Mountains are a north-trending mountain range located in southwestern Montana with a topographic relief of nearly 1500 m along its western margin. The range is flanked by broad intermontane basins on the east and west, and many peaks have elevations exceeding 3100 m; the highest is Mt. Jefferson which has an elevation of 3181 m.

The Tobacco Roots possessed considerable relief by the Late Cretaceous - early Tertiary (70-60 Ma) (Schmidt, 1975). Today the mountains are essentially an east-tilted block uplift which has been raised along a high-angle normal fault located on the western margin of the range. This present uplift began in the late Miocene (10 Ma) and is still taking place (Pardee, 1950).

Rocks exposed in the Tobacco Roots span the Precambrian to the Quaternary, but the core of the range consists primarily of Archean gneisses and a Cretaceous pluton. Archean rocks (older than 2500 Ma) dominate the northern, western, and southern parts of the Tobacco Roots whereas granitic to dioritic intrusives of the Late Cretaceous (77-72 Ma) Tobacco Root batholith constitute the central and eastern parts of the range (Vitaliano and others, 1976). Paleozoic sedimentary rocks are present along the northern and northwestern margins and have an minimum aggregate thickness of 1700 m (5600 ft). These once covered the central core of the range but have been eroded due to uplift.

Precambrian Rocks

The Late Archean rocks of the Tobacco Root Mountains can be subdivided into five categories. Those rocks located in the west-central and southern areas consist of quartzofeldspathic gneiss, hornblende gneiss, dolomitic marble, aluminous schists, quartzite, and iron formation. This diverse lithologic assemblage was first mapped by Levandowski (1956), Burger (1966), and Cordua (1973). For the purposes of this project it is referred to as the Indian Creek Metamorphic Suite (ICMS) (Fig. 1).

Rocks exposed in the north and northwest were mapped by Reid (1957), Root (1965), and Hanley (1975). These are dominated by quartzofeldspathic gneisses with lesser amounts of hornblende-plagioclase gneiss and amphibolite. These are referred to as the Pony - Middle Mountain Metamorphic Suite (PMMMS).

Located structurally above the ICMS and below the PMMMS in the west-central Tobacco Roots is a distinct lithologic assemblage consisting of amphibolite, hornblende-plagioclase gneiss, anthophyllite/gedrite-garnet-plagioclase gneiss, sillimanite schist, and quartzite. These rocks were first mapped as a distinct assemblage by Burger (1966) who referred to them as the anthophyllite-gneiss assemblage. Subsequently, Gillmeister (1971) mapped the same rocks in detail and referred to them as the Spuhler Peak Formation (SPF).

Metabasite sills and dikes are present as a minor constituent within all Archean exposures with the important exception of the SPF. Finally, all lithologic assemblages contain occasional exposures of meta-ultramafic rocks.

Three separate sets of Proterozoic diabase dikes are exposed throughout the Archean rocks but are mainly present in the southern areas.

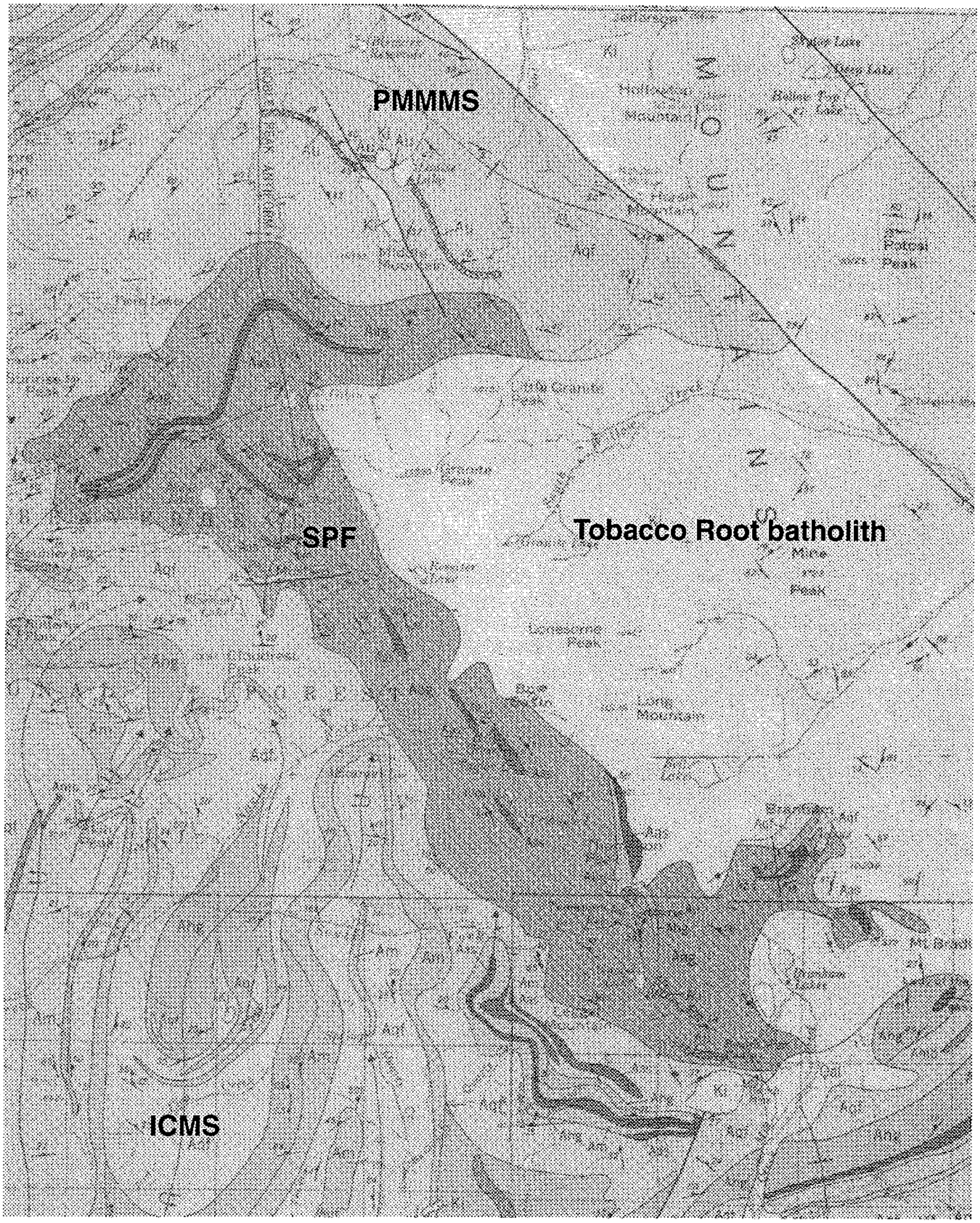

Figure 1. A portion of a geologic map of the Tobacco Root Mountains showing the dominant north-south trending folds in the ICMS and distribution of the SPF (Vitaliano and others, 1979).

Protoliths of Archean Rocks

The interlayered sequence of marble, quartzite, iron formation, and sillimanite schist has an obvious sedimentary parentage. As the boundaries of these units everywhere conform to those of interlayered quartzofeldspathic gneiss and hornblende gneiss, the protolith of the vast majority of rocks within the ICMS likely was a sequence of marine sedimentary rocks with interlayered extrusive volcanics. Grain-shape studies of zircons from the quartzofeldspathic gneisses (Hess, 1967; Cordua, 1973) as well as limited chemical information support a sedimentary origin for at least some of the quartzofeldspathic rocks.

As very minor amounts of marble and quartzite are present in the PMMMS it seems that at least some of this assemblage also has a sedimentary parentage. However, metamorphosed plutonic rocks of similar age to the Archean rocks in the Tobacco Roots are present in virtually all adjacent mountain ranges. This fact plus the widespread homogeneity of the quartzofeldspathic gneisses in the PMMMS suggest that an intrusive parentage for a significant portion of these gneisses is a distinct possibility.

The exact protolith for the SPF is not yet clear, but the intimately interlayered character of the assemblage which is dominated by amphibolites interspersed with quartzite, sillimanite schist, and other gneisses suggests a large component of mafic extrusives and minor amounts of other marine sediments. The metabasites clearly represent igneous intrusives, and the meta-ultramafics may represent tectonic slices. However, the details of their origin are still not resolved.

Structural Relationships

Map patterns demonstrating an early phase of isoclinal recumbent folds are present at only a few isolated localities in the Tobacco Roots. These are particularly evident at two localities in the southern exposures (Cordua, 1973) and can be inferred from the regional map pattern of marbles in the west-central region (Burger, 1966, 1967, 1969). Reid (1957) noted this early phase in outcrop-scale folds as have all other workers in this range. These folds are interpreted as the earliest folding phase that can be distinguished and may be connected to the generation of the dominant foliation observed in the Archean rocks of the Tobacco Roots.

The dominant folds of the west-central and southwestern regions are a series of upright, sub-isoclinal folds that plunge variably to the north-northwest, north, or north-northeast at gentle angles and are most commonly overturned to the east (Fig. 1). These structures clearly and consistently deform the dominant foliation ascribed to the earlier recumbent folds.

The final, clearly demonstrable separate period of folding consists of broad, open folds that plunge gently to the north. These are typified by the Noble Peak Antiform as mapped by Reid (1957) but also are developed in individual outcrops.

A major set of faults trends northwest-southeast and has both dip-slip and strike-slip components. These date from the Precambrian as they controlled emplacement of Proterozoic dikes which have a similar orientation and were reactivated during the Laramide deformation as they offset batholith contacts. A subsidiary sets of faults of northeast trend also were active during the Laramide as they offset batholith contacts and the northwest-trending faults. The time of origin of these faults is unclear (Vitaliano and others, 1979).

Metamorphism and Geochronology

The majority of the Archean rocks contain mineral assemblages typical of the upper amphibolite facies which were formed at conditions of 650-750° C and 4-6 kilobars (Immega and Klein, 1976). Some rocks, however, contain assemblages consistent with lower granulite facies conditions. Textural evidence exists that suggests an earlier granulite-grade metamorphism was overprinted by an amphibolite-grade event, but there also is evidence that granulite-grade levels were achieved locally during an amphibolite-grade event. A minor retrograde metamorphism of greenschist-facies level was developed locally in shear zones, faults, and at igneous contacts and usually is ascribed to Laramide effects, but this age is not definite.

The oldest published age date determined for Archean rocks of the Tobacco Root Mountains is 2700 Ma (Mueller and Cordua, 1976; James and Hedge, 1980) which is correlated with an upper amphibolite facies metamorphic event. Clear evidence also exists for a widespread thermal event in the region at 1800-1600 Ma (Giletti, 1966; O'Neill and others, 1988). Crystallization ages as old as 3300 Ma (Mueller and others, 1993) have been determined for tonalitic and trondhjemitic gneisses in the southern Madison Range, but rocks this old have not as yet been published for the Tobacco Roots. However, unpublished dates in the range 3400-3100 Ma have been determined for detrital zircons from quartzites in the ICMS (Mogk, personal communication). These document the exposure of an older crust at that time and limit the age of the metamorphism of ICMS rocks to younger than 3100 Ma.

Project Goals and Strategies

The goal of the Montana Archean Rocks Project was to clarify the relationship between the SPF and the ICMS. Burger (1966, 1967, 1969) interpreted the contact between these two assemblages as a fault based on the observation that the Spuhler Peak apparently truncates the large, regionally developed folds in the Indian Creek rocks and what he perceived as different metamorphic histories in the two groups of rocks. Gillmeister (1971), however, interpreted the contact as an unconformity and believes that the SPF overlies both the ICMS and the PMMMS. Gillmeister noted, as have others, that metabasites are present in both of these suites but are not present in the SPF.

Cummings and McCulloch (1992) mapped a series of shear zones that separate the SPF from the ICMS in a small area near Branham Lakes, located in the southeastern-most part of the area mapped by Burger. One of their shear zones coincides with his fault location, and they interpret the SPF as a sliver of oceanic crust thrust against shelf sediments (Indian Creek Metamorphic Assemblage). Understanding the actual relationship between the Spuhler Peak and Indian Creek rocks is crucial to unraveling the Archean and Proterozoic history of southwestern Montana, especially if the Spuhler Peak rocks represent allochthonous oceanic crust.

The contact between the SPF and ICMS and excellent sequences of Spuhler Peak rocks are well exposed along three drainages in the west-central Tobacco Root Mountains - the Mill Creek drainage (especially at Branham Lakes), the Indian Creek drainage, and the Wisconsin Creek drainage (especially Noble Fork of Wisconsin Creek near Noble Lake). Accordingly, student projects were selected from all three locations.

Student Research Topics

In order to meet the goal of this research endeavor, project participants undertook a wide variety of studies. These include:

(1) A detailed study of contact relationships between the SPF and the ICMS. Lisa Jacob (Smith College) worked on this topic with regard to rocks exposed at Noble Lake, and Toby King (Amherst College) is undertook a similar study in the Branham Lakes area. Lisa and Toby also obtained $^{40}Ar/^{39}Ar$ dates from amphibolites in both rock suites.

(2) A comparison of mineralogy and metamorphic history in rocks of similar bulk compositions from each rock suite. Robin Fisher (Smith College) studied aluminous schists and Pamela Cady (Colorado College) worked on amphibolites.

(3) A close examination of rock types in the SPF in the three areas of best exposure in order to characterize as fully as possible this unique assemblage of lithologies. Chris Poulson (Carleton College) worked on Brahman Lakes rocks, Kara Tierney (Amherst College) worked on Indian Creek rocks, and Josh Lowell (Colorado College) worked on Noble Lake rocks.

(4) Due to several unique mineral assemblages in Spuhler Peak rocks, two students undertook petrologic and geochemical studies in the hopes of obtaining geothermometry and geobarometry constraints as well as protolith constraints. William Peck (Beloit College) worked on anthophyllite/gedrite-bearing rocks, and LeAndra Archuleta (Pomona College) studied garnet-cordierite relations.

(5) Jennifer Sincock (Franklin and Marshall College) focused on a "disturbed" zone of intense folding within the SPF that may represent a zone of concentrated shear during emplacement of thrust slices.

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Geologists familiar with the Archean geology of this part of Montana (David Mogk, Montana State University; Daryl Henry, Louisiana State University; and Michael O'Neill, U.S. Geological Survey) worked with us for two days in the Branham Lakes and Indian Creek areas, and we are grateful for their help and insights. Student sponsors who visited the field area include Edward Beutner (Franklin & Marshall College), Tekla Harms (Amherst College), Eric Leonard (Colorado College), and Stephen Weaver (Beloit College). These individuals were especially helpful in supporting their students' field work, and project faculty found the visitors' observations and geological expertise especially valuable.

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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.