Archean Rocks of the Tobacco Root Mountains, Montana

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5), particularly in their high LILE abundances and high Ba/Nb and Rb/Nb ratios. I-type silicic magmas are mostly found at convergent plate margins, including oceanic and continental magmatic arc settings (Christiansen and Keith, 1996). The nearby, and presumably not much younger, Boulder Creek-age plutons are characteristically I-type granodiorite and tonalite, also suggestive of arc settings. Finally, comparison with an extensive numerical data set for subalkaline silicic obsidians shows the ranges and averages of most trace elements in the Arkansas River rocks are consistent with those for mature island arcs and active continental margins (MacDonald and others, 1992).

While not the major emphasis of this study, the four mafic volcanic samples analyzed all plot as calc-alkaline basalts from a volcanic arc setting using the TiO₂ - P₂O₅ - MnO discriminant diagram of Mullen (1983).

**DISCUSSION AND CONCLUSIONS**

The nearest well studied sequence of bimodal metavolcanic rocks occurs approximately 15 km west of the westernmost samples in the present report, near the town of Salida (Boardman and Condie, 1986). The felsic units of the Arkansas Canyon strongly resemble those of Salida (Fig. 4), dated at 1728 +/- 5 Ma, with REE values falling almost entirely within the spread of the Salida aphyric felsic volcanic data. As in the Salida suite, Sr values are too low and heavy REEs are too enriched to suggest a petrogenetic origin involving partial melting of continental crust (Boardman, 1986). The 1770 - 1760 Ma Dubois Greenstone volcanic belt, located approximately 130 km to the west near the town of Gunnison, also has similar trace element abundances, and is compositionally comparable to bimodal volcanics found in continental margin arcs and associated back-arc basins (Condie, 1986). Comparisons with the Salida and Gunnison Early Proterozoic volcanics and with I-type rhyolites defined by Christiansen and Keith (1996) suggest that the bimodal Arkansas Canyon suite is a remnant of a young back-arc basin developing on or near continental crust. The extent of bimodal volcanics within the region is much greater than previously thought: clearly these rocks have a significant role in the geologic history of the Arkansas River canyon and in the geologic assembly of southwestern North America.

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Archean and Proterozoic history of metamorphic rocks, Tobacco Root Mountains, southwestern 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 the western margin. These mountains are 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 (Pardoe, 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 a minimum aggregate thickness of 1700 m (5600 ft). These once covered the central core of the range but have been eroded following uplift.

PRECAMBRIAN ROCKS
The Late Archean rocks of the Tobacco Root Mountains are 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). They are dominated by quartzofeldspathic gneisses with lesser amounts of hornblende-plagioclase gneiss and amphibolite. These rocks are referred to here as the Pony - Middle Mountain Metamorphic Suite (PMMS).

Located structurally above the ICMS and below the PMMS in the west-central Tobacco Roots is a distinct lithologic assemblage consisting of amphibolite, hornblende-plagioclase gneiss, 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). For consistency, these rocks are herein referred to as the Spuhler Peak Metamorphic Suite (SPMS).

A suite of metamorphosed mafic dikes and sills (MMDS) provides a possible key to unraveling the metamorphic and structural history of the Archean rocks. The MMDS cut across the strongly developed gneissic banding and clearly post-date its formation (Fig. 2). However, these metamorphosed intrusives were subjected to a high-grade metamorphic
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 SPMS and PMMS (Vitaliano and others, 1979).
event and a penetrative deformation. The MMDS are present in the ICMS and the PMMMS but to date have not been found in the SPMS, even though they are abundant in areas quite close to the contact between the ICMS and PMMMS with the SPMS.

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

![Figure 2. A metamorphosed mafic dike (MMDS) cutting across well-developed gneissic banding in gneisses of the PMMMS. Here the dike contains a faint but distinct foliation parallel to its contact with the gneiss and contains the assemblage garnet-clinopyroxene-hornblende-plagioclase.](image)

**PROTOLITHS OF ARCHEAN ROCKS**

**ICMS:** The marble, quartzite, iron formation, and sillimanite schist units in the ICMS have 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 was believed to primarily represent a sequence of marine sedimentary rocks with possible interlayered extrusive volcanics. Grain-shape studies of zircons from the quartzofeldspathic gneisses (Hess, 1967; Cordua, 1973) as well as limited chemical information supported a sedimentary origin for at least some of the quartzofeldspathic rocks. However, chemical analyses of ICMS mafic and felsic gneisses by Jacob (1994), Martin (1996) and Abeyta (this volume) suggest that a significant percentage of these gneisses may have an igneous parentage.

**PMMMS:** 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. Discriminant diagrams based on chemical analyses by Pufall (1996) and Abeyta (this volume) support an igneous origin for their samples. This fact plus the widespread homogeneity of the quartzofeldspathic gneisses in the PMMMS suggest that an igneous parentage for a significant portion of these gneisses is a distinct possibility. A few isolated, discontinuous exposures of ICMS-like gneisses in the PMMMS could possibly represent roof pendants.

**SPMS:** The exact protolith for the SPMS is not yet certain, but the intimately interlayered character of the assemblage which is dominated by amphibolites and orthoamphibolites interspersed with quartzite, sillimanite schist, and other gneisses suggests a large component of mafic extrusives and minor amounts of other marine sediments. Work
by Peck (1994), Sincock (1994), Poulsen (1994), Puffall (1996), and Cox (1996) demonstrates that the amphibolites and orthoamphibolites represent tholeiitic basalts, komatiitic basalts, and komatiites (Fig. 3). As the quartzite and schists may represent metamorphosed cherts and shales, it appears likely that the SPMS is a segment of metamorphosed oceanic crust.

Others: Whole-rock geochemistry suggests that the meta-ultramafics have komatiitic affinities as defined by the MgO content (20-41 wt.%) and discriminant diagram relationships for Ti, Zr, Y, and Sr. This is consistent with an ocean floor origin. The metamorphosed mafic dikes and sills (MMDS) clearly represent igneous intrusives.

![Spuhler Peak Metamorphic Suite](image)

**Figure 3.** Jensen cation plot (Jensen, 1976) for selected rocks of the SPMS suggesting some have komatiitic and basaltic komatiite affinities. Analyses: 64 this study, 20 from Cummings and McCullough (1992), and 6 from Friberg (1976).

**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 have been described as a series of upright, sub-isoclinal folds (based on discontinuous outcrops of marker horizons) 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. 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.

Outcrop scale folds are common in both the SPMS and ICMS. These folds range in style from open-to-closed, concentric folds to tight-to-isoclinal similar folds. Most of these folds are cylindrical with straight fold axes that lie in a dispersed pattern. Some of these folds are sheath folds with strongly curved fold axes (Fig. 4). Their curvature outlines a dispersed pattern which reproduces that of the cylindrical folds (King, 1994). These types of patterns elsewhere have been interpreted as indicative of simple shear deformation (Mies, 1991, and references
The dispersed fold axis pattern is deflected by outcrop-scale, third-generation, broad, open folds. If simple shear did occur in the Tobacco Roots, it predated the final period of folding.

In map pattern, the SPMS/ICMS contact mimics the cross-sectional shape of tight-to-isoclinal, similar, outcrop-scale folds (Owen, 1996; Kranenberg, 1996). This raises the testable hypothesis that the SPMS/ICMS contact experienced an episode of regional simple shear and related folding. Kranenberg's (1996) results from quartz petrofabric support the presence of penetrative simple shear on a microfabric scale.

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. The faults 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; these offset batholith contacts and the northwest-trending faults. The time of origin of these faults is unclear (Vitaliano and others, 1979).

Figure 4. A magnificent sheath fold developed in amphibolite within SPMS rocks.

METAMORPHISM

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). Indeed, preliminary geothermobarometry reported by by King (1995), Archuleta (1994), Tierney (1994) and Cheney et al. (1995) of near-rim compositions from a variety of rock types reflect temperatures of 650-700 °C and pressures of 5-7 kilobars. Some rocks from two of the three main lithologic packages and from the MMDS, however, contain orthopyroxene + plagioclase-bearing assemblages consistent with lower granulite facies conditions. Textural evidence presented by Tierney (1994) and Archuleta (1994) suggests that an earlier high pressure (kyanite + potassium feldspar or kyanite + gedrite) metamorphism was overprinted by a lower pressure amphibolite-grade (sillimanite + cordierite) event. However, there also is evidence that granulite-grade levels were achieved locally during the lower pressure amphibolite-grade event. Minor retrograde metamorphism at greenschist-facies conditions was developed locally in shear zones, faults, and at igneous contacts and usually has been ascribed to Laramide effects, but this age is not definite.

GEOCHRONOLOGY

The most commonly cited age date determined for Archean rocks of the Tobacco Root Mountains is 2700 Ma
(Mueller and Cordua, 1976; James and Hedge, 1980) which these authors correlated with an upper amphibolite facies metamorphic event. 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 ages this old have not as yet been published for the Tobacco Roots. However, unpublished dates as old as 3900 Ma have been determined from cores of detrital zircons from quartzites in the ICMS (Mogk, personal communication). These zircon cores have overgrowths which yield dates in the 3300 - 3100 range and, therefore, document a high-grade metamorphic event in the Tobacco Roots at this time.

Recently, Krogh et al. (1997) published a Pb/U age of 2400 Ma based on partial resetting of zircons in a PMMMS gneiss. Similar ages are present elsewhere in the region and suggest that the whole rock age of 2700 Ma may be a hybrid from 3100 and 2400 Ma events.

Evidence also exists for a widespread thermal event in the region at 1800-1600 Ma (Gillett, 1966; O’Neill and others, 1988). Nine total fusion $^{40}$Ar/$^{39}$Ar ages on amphiboles from ICMS metasomorphosed mafic dikes and SPMS and ICMS amphibolites (Jacob, 1994; King, 1994; Brady et al., 1994) give a mean age of 1700 Ma. It is clear that these Archean rocks were subjected to temperatures (approximately 520°C or higher) sufficiently high to reset amphibole argon ages in the Proterozoic. This event has not as yet been correlated with any structural or metamorphic event recognized in the Archean rocks.

**PROJECT GOALS AND STRATEGIES**

The initial and continuing goal of the Montana Archean Rocks Project is to clarify the relationship between the SPMS 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 SPMS overlies both the ICMS and the PMMMS. Gillmeister (1972) noted, as have others, that the metamorphosed mafic dikes and sills (MMDS) are present in both of these suites but are not present in the SPMS.

Cummings and McCulloch (1992) mapped a series of shear zones that separate the SPMS 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 SPMS as a sliver of oceanic crust thrust against shelf sediments (ICMS).

Based on these observations, student research projects in 1993/94 concentrated on SPMS geochemistry and metamorphic petrology, comparative petrology of aluminous schists and amphibolites in the SPMS and ICMS, structural relationships along the contact between the SPMS and ICMS, $^{40}$Ar/$^{39}$Ar ages on amphiboles from ICMS metasomorphosed mafic dikes and sills and SPMS and ICMS amphibolites, and geochemistry of ICMS quartzofeldspathic gneisses (see previous discussion).

Geologists familiar with these suites of rocks believe the Spuhler Peak Metamorphic Suites has experienced a different structural and metamorphic history than the Indian Creek Metamorphic Suite and the Pony-Middle Mountain Metamorphic Suite (Mogk, 1993, and O’Neill, 1993, personal communication). Understanding the actual relationship between these three suites of rocks is crucial to unraveling the Archean and Proterozoic history of southwestern Montana in view of our belief that the Spuhler Peak rocks represent allochthonous oceanic crust (Brady et al., 1994). Therefore, the 1995/96 Montana Archean Rocks Project sought to build on the findings of the 1993/94 project by further clarifying the relationships between the Spuhler Peak Metamorphic Suite, the Pony-Middle Mountain Metamorphic Suite, and the Indian Creek Metamorphic Suite. It also became clear in 1993/94 that the metamorphosed mafic dikes and sills and meta-ultramafic rocks may hold the key to understanding the tectonic history of these Archean rocks, so some projects tackled these rocks.

The 1997 field season of the Montana Archean Rocks Project was designed in an effort to bring this project to closure. Therefore, project faculty selected student projects based on those topics most urgently requiring further study. The main goals were:

1. to obtain detailed information using petrography, mineral chemistry and zoning, reaction textures, and geothermobarometry for the SPMS, the PMMMS, the ICMS, and the MMDS in order to determine similarities and differences in their p-T history;

2. to complete our geochemical studies of the various metamorphic suites, primarily for protolith determination;

3. to continue to document structural fabrics to determine if differences exist between the SPMS and other suites. This hopefully will help elucidate the nature of the SPMS contact and the relative time of emplacement of the SPMS if it is indeed allochthonous; and
(4) to obtain age dates for the MMDS, melt zones in boudinage in SPMS rocks, and detrital zircons in quartzites from the SPMS. This goal is being pursued by project faculty.

**STUDENT RESEARCH TOPICS**

Student research efforts during the summer of 1997 and in subsequent months include: (1) comparison of geothermobarometry of metamorphosed mafic dikes and sills with results from major rock suites- Sarah Carmichael, Smith College; (2) petrology and geothermobarometry of the aluminous rocks in the SPMS and the ICMS - Brian Monteleone, College of Wooster; (3) petrology and geothermobarometry of garnet amphibolites across the Tobacco Roots in the SPMS and the PMMMS - Kurt Steffen, Carleton College; (4) petrology and geothermobarometry of garnet amphibolites across the Tobacco Roots in the ICMS and the PMMMS - Jessica Frisch, Amherst College; (5) petrology and geothermobarometry of orthopyroxene-bearing (granulite facies) rocks in the ICMS - Christine Hatch, Amherst College; (6) whole rock geochemistry of the MMDS - Caroline Harris, Pomona College; (7) whole rock geochemistry of quartzofeldspathic gneisses in the PMMMS and ICMS - Reyna Abeyta, Colorado College; (8) quartz petrofabrics from quartzites in all major suites - Daniel Blednick, Amherst College; and (9) calcite petrofabrics from marbles in the ICMS - Carlos Picornell, University of New Orleans.

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Looking north from Noble Lake at terrain underlain by SPMS rocks believed to represent allochthonous oceanic crust.
A Geochemical and Petrographic Analysis of quartzofeldspathic gneisses in the Pony Middle Mountain Metamorphic Suite and Indian Creek Metamorphic Suite, Tobacco Root Mountains, Southwestern Montana

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INTRODUCTION
The Indian Creek Metamorphic Suite (ICMS), located in the west-central and southern areas of the Tobacco Root Mountains contains quartzofeldspathic gneiss, hornblende gneiss, dolomitic marble, aluminous schists, quartzite and iron formation. The Pony Middle Mountain Metamorphic Suite (PMMMS), located in the north and northwest Tobacco Root Mountains, is dominated by quartzofeldspathic gneiss with lesser amounts of hornblende-plagioclase gneiss and amphibolite.

The ICMS and PMMMS quartzofeldspathic gneisses occur within notably differing rock associations. Generally, quartzofeldspathic gneisses of the ICMS include a large amount of isoclinally folded marbles and quartzites along with a variable amount of hornblende gneiss. The PMMMS quartzofeldspathic gneiss includes only a very minor amount of these marbles, quartzites and hornblende gneisses. The presence of marble and quartzite in the ICMS, suggests it is more likely to be of sedimentary origin than the PMMMS. This lithologic discrepancy provides the question addressed in this study. The goal of this project is to determine the protolith of these quartzofeldspathic gneisses and to make a geochemical comparison between the ICMS and PMMMS assemblages.

METHODS
Eighty-two samples of quartzofeldspathic gneiss were collected in the field for geochemical and petrographic analysis. From these eighty samples thirty thin sections were cut for petrographic analysis. Fifteen samples were analyzed for major, minor and trace element data; six from the ICMS, and nine from the PMMMS. These sample localities were chosen based on their proximity to other mapped lithologic units, such as marbles, quartzites, hornblende gneisses. Major and minor element data were analyzed using Inductively Coupled Plasma (ICP) methods performed by ACT Labs in Ontario, Canada. Trace elements were analyzed by using Instrumental Neutron Activation Analysis (INAA) performed at Oregon State University.

PREVIOUS WORK
Several attempts have been made at determining the origin of the quartzofeldspathic gneisses in the Tobacco Root Mountains. Unfortunately, the interpretations are generally conflicting and inconclusive. Several high grade metamorphic and folding events have obliterated the primary textures and structures that might provide a clue to the origin of these rocks.

The ICMS quartzofeldspathic gneisses contain a significant amount of interfoliated and folded marble and quartzite. Due to the spatial relationship, the rocks have generally been interpreted as sedimentary (Mogk et al., 1992). In addition, grain shape studies on zircons performed by Cordua (1973) and Hess (1967) indicate that 72-100% of the zircons found in these gneisses are rounded. The rounded shape of these zircons suggested they could be detrital grains of sedimentary origin.

In contrast, geochemical analysis of quartzofeldspathic gneisses in the ICMS conducted by Jacob (1984) suggests that the quartzofeldspathic gneisses of this region are igneous in origin based on discrimination functions of Shaw (1972). Also, Wilson and Hyndman (1990) conducted studies on four gneisses from the Copper Mountain and Kelley area. From these studies they concluded that these gneisses show calc-alkaline affinities similar to granitic rocks enclosing synplutonic basaltic dikes found in the Cretaceous Idaho Batholith and could have developed in a similar setting. In addition, Clark and Mogk (1986) found that REE evidence for quartzofeldspathic gneisses in the nearby Blacktail range are consistent with tonalitic and granitic source areas.