# PROTOLITH AND TECTONIC SETTING OF QUARTZOFELDSPATHIC GNEISSES OF THE HIGHLAND MOUNTAINS, GREENHORN RANGE AND ALDER GULCH; SOUTHWEST MONTANA

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## INTRODUCTION

Precambrian rocks in southwest Montana are exposed in a series of block-fault mountain ranges that trend north-south. The Tobacco Root Mountains are a member of this series and were the subject of previous Keck projects and a GSA Special Paper (Brady et al., 2004), which showed that the range underwent two major metamorphic events: a previously known Archean orogeny and a newly characterized Proterozoic event at 1.8-1.7 Ga termed the Big Sky Orogeny.

Quartzofeldspathic gneisses, most thought to be Archean in origin, are the dominant Precambrian lithology of the region (Mogk et al., 2004). Based on geochemical, petrologic, and field evidence, Mogk and others classified the quartzofeldspathic gneisses of the Tobacco Root Mountains as felsic members of one or more bimodal volcanic associations extruded in an active continental margin or continental arc setting.

West of the Tobacco Root Mountains, the Highland Mountains, Alder Gulch, and the Greenhorn Range lie in approximate north-to-south succession and also contain quartzofeldspathic gneisses as the dominant Precambrian lithology. This study attempts to establish the protolith and tectonic setting of the quartzofeldspathic gneisses of these three regions and compares them with Mogk and others' results in the Tobacco Root Mountains.

## METHODS

Fieldwork was conducted for four weeks in summer 2005 in areas previously mapped as quartzofeldspathic gneiss (O'Neill et al., 1996; Kellogg and Williams, 2000). Fifty-four samples were collected and located in the field on a 1:1000 topographic map using GPS. Twenty-two samples were prepared and studied in thin section, and twenty-one samples were pulverized and sent to Acme Geochemical in Vancouver, B.C. for geochemical analysis. Abundances of major oxides and minor elements were analyzed by ICP-emission spectrometry, and abundances of rare earth and refractory elements were analyzed with ICP mass spectrometry.

## FIELD DESCRIPTION

Quartzofeldspathic gneisses of the Highland Mountains and Alder Gulch are typically interlayered with amphibolites (Siegel, this volume) and cut by metamorphosed mafic dikes and sills (Moore, this volume). In the northeast part of the Highland Mountains, quartzofeldspathic gneisses form a doubly-plunging antiform termed the Highland Gneiss Dome (HGD; O'Neill et al, 1988). The inner core of the HGD consists of quartzofeldspathic gneiss that is leucocratic, medium- to coarse-grained, strongly deformed, and massive to weakly layered; O'Neill and others (1996) mapped this unit and termed it X(A)q. The outer core of the HGD, the X(A)qf unit, consists of quartzofeldspathic gneiss that is similar to that of the inner core but is darker and has platy foliation due to the increased presence of biotite and minor hornblende. Structurally above the core of the HGD, the X(A)gb and X(A)m units form part of the dome's cover. The X(A)gb unit is medium- to very coarse-grained garnet-biotite gneiss and the X(A)m unit is mylonitic medium- to coarse-grained biotite gneiss commonly with sheared and drawn-out quartz and feldspar grains.

Samples from Alder Gulch were taken near the east side of Montana Route 287 between the towns of Alder and Nevada City. Quartzofeldspathic gneisses and amphibolites are interlayered with a periodicity on the order of tens of meters (Siegel, this volume). The gneisses are leucocratic, medium- to coarse-grained, compositionally banded and contain minor garnet and biotite.

Samples from the Greenhorn Range were taken 15 kilometers southwest of the Alder Gulch samples, west of Montana Route 287. Gneisses of the Greenhorn Range are medium- to coarse-grained and distinctly foliated. Bands of quartz, potash feldspar, plagioclase, and dark minerals alternate on the scale of a few millimeters. Garnet is present in some samples.

# PETROGRAPHY

The X(A)q unit of the Highland Mountains contains 50 to 80% quartz and 20 to 40% anhedral plagioclase (oligoclase), with the exception of one sample (30% quartz, 60% plagioclase). Biotite (1-7%) defines foliation. The unit also contains chlorite (<3%), muscovite (<1%), and in one sample, epidote. Quartz grains are commonly elongated parallel to biotite foliation. The X(A)qf unit contains 60 to 80% quartz, 7 to 25% plagioclase (calcic oligoclase to sodic andesine), and <3% microcline. Biotite (4 to 20%) defines foliation, which is in places interrupted by plagioclase phenocrysts up to 1 cm in diameter. Muscovite (1-2%) and garnet (1-3%) are also present in X(A)qf samples. Only one sample from the X(A)gb unit was studied; it contains 40% quartz, 40% anhedral plagioclase, 20% biotite, and <2% garnet. The one petrographically-analyzed sample from X(A)m, the other unit in the cover of the Highland Gneiss Dome, contains 60% quartz, 20% biotite, 10% plagioclase (oligoclase), 3% garnet, and 3% microcline. Quartz, feldspar, and garnets are jagged and fractured, indicating the cataclastic history of this unit. Biotite exhibits preferred orientation that parallels the direction of elongation of the quartz grains. This study does not characterize X(A)gb or X(A)m, but one sample of each unit was included to represent a broader range in the magma series.

Quartzofeldspathic gneisses of Alder Gulch contain 15 to 70% quartz. Unlike the Highland Mountains gneisses, the predominant feldspar in Alder Gulch samples is microcline (25 to 60%). Alder Gulch gneisses contain less than 10% plagioclase, and less than 2% each of garnet and biotite. Epidote is commonly a trace mineral.

Samples from the Greenhorn Range contain 25 to 50% quartz, 30 to 45% microcline, and 2 to 25% plagioclase (oligoclase to andesine), and a trace to 1% garnet. Dark minerals, which exhibit preferred orientation, include biotite (1 to 10%) and hornblende (1 to 5%). Apatite and

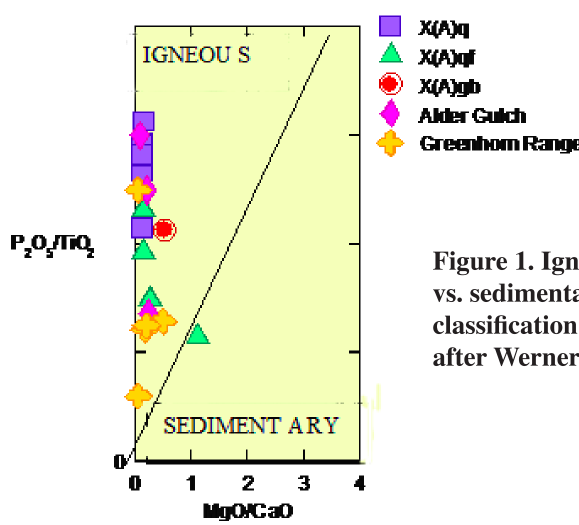


**Figure 1. Igneous vs. sedimentary classification diagram after Werner (1987)**

epidote are trace minerals.

# GEOCHEMISTRY

Twenty-one samples were analyzed with ICP-MS for major, trace, and rare earth element compositions. Ten samples were analyzed from the Highland Mountains units—four X(A)qf, five X(A)q, and one X(A)gb. Six were analyzed from Alder Gulch and five from the Greenhorn Range. The gneisses range in $SiO_2$ composition from 67 to 76%, with the exception of the X(A)gb sample (60% $SiO_2$). Geochemical data indicate that the protolith of the gneisses was igneous (Fig. 1; Werner (1987)). Samples plot in the rhyolite or rhyodacite/dacite fields of the igneous classification diagram of Winchester

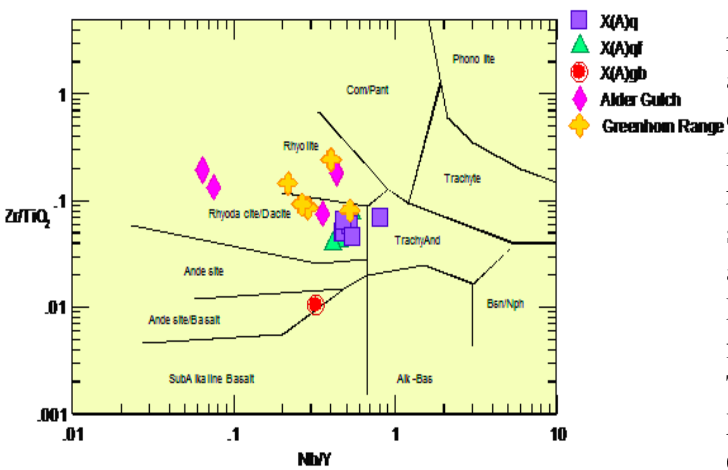


**Figure 2. Igneous classification diagram after Winchester and Floyd (1977).**

Samples from the Highland Mountains and Greenhorn Range are typically enriched in REEs compared to chondrites (Fig. 3); only the HREE values of X(A)q samples were near chondrite values. The REE plot has a negative slope indicative of LREE-enrichment in an evolved magma. Most Alder Gulch and Greenhorn Range samples have pronounced negative Eu anomalies, which indicate early fractionation of plagioclase. Samples from the Highland Mountains have either slightly negative, slightly positive, or no Eu anomalies.

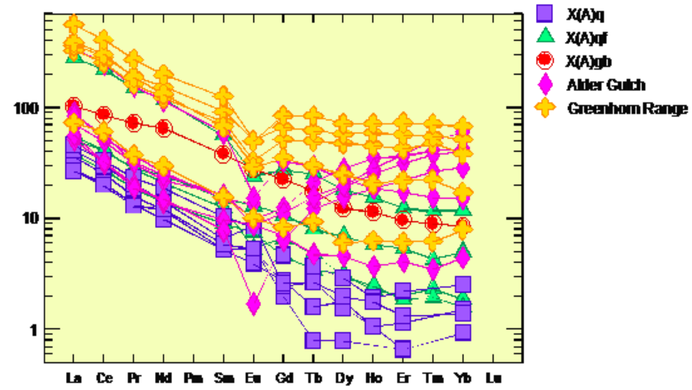


**Figure 3. Rare earth element plot normalized against chondrites after Sun and McDonough (1989).**

As shown in Figure 4, the gneiss samples are typically enriched in LILEs compared to primitive mantle, a signature consistent with volcanic arc magmas. Samples from all three regions have negative P, Nb, and Ti anomalies and positive K and Pb anomalies. Relative depletions of Ti-group elements are thought to indicate a volcanic arc setting, resulting from retention of these elements in the subducting slab from which the magma derives. Sr anomalies are negative in samples from the Highland Mountains and positive in samples from the Greenhorn Range and Alder Gulch. The anomalies are most pronounced in the X(A)q unit, which plots with notable cohesion. Of the samples with measurable amounts of Ta, the Ba/Ta ratio is greater than 1000. A Ba/Ta ratio greater than 450 is characteristic of a volcanic arc, but not backarc magma (Gill, 1981).

Data from the Highland Mountains consistently cluster within the volcanic arc field of tectonic discriminant diagrams after Pearce et al. (1984; Fig. 5). Samples from Alder Gulch and the Greenhorn Range are distributed near the junction of the volcanic arc, syn-collisional, and within-plate fields.

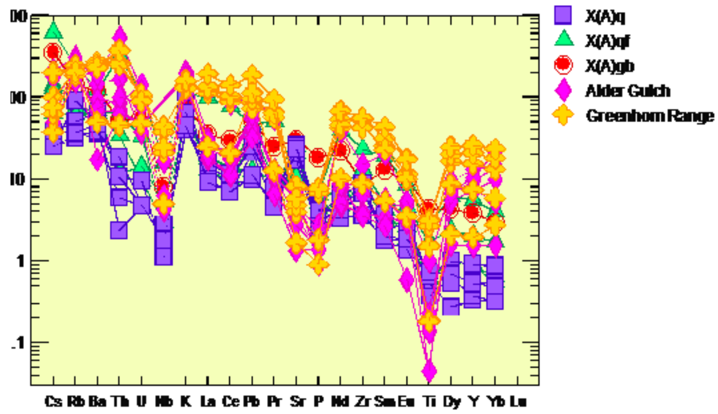


**Figure 4. Spider diagram normalized against primitive mantle after Sun and McDonough (1989).**

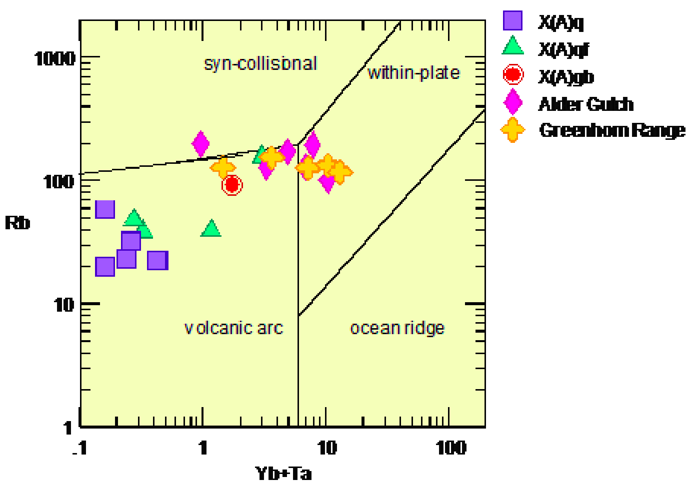


**Figure 5. Tectonic discriminant diagram after Pearce et al. (1984).**

# COMPARISON WITH QUARTZOFELDSPATHIC GNEISSES OF THE TOBACCO ROOT MOUNTAINS

Based on field relations, geochemical discriminant analysis, and isotopic systematics, Mogk and others (2004) found that the quartzofeldspathic gneisses and interlayered metamorphosed mafic rocks of the Tobacco Root Mountains have igneous protoliths and are derived from a bimodal volcanic suite that was produced ca. 3.3 Ga. They distinguish between metamorphic mafic rocks (<52% $SiO_2$), intermediate gneisses (52-65% $SiO_2$), and felsic gneisses (>65% $SiO_2$). The felsic gneisses are classified as granitic (potassic, $K_2O/Na_2O>1$) or tonalitic (sodic, $K_2O/Na_2O<1$), with no intended genetic interpretations.

The $SiO_2$ content of gneisses of the present study, with the exception of the X(A)gb sample (60% $SiO_2$), is comparable to that of the felsic gneisses of the Tobacco Root Mountains. Using Mogk's criteria, samples from the Highland Mountains are "sodic" and samples from Alder Gulch and the Greenhorn Range are "potassic," with the exception of one sample in each category. Felsic gneisses of both studies generally plot in the calc-alkaline field of an AFM diagram (not shown).

Sodic gneisses of the Tobacco Root Mountains, like gneisses from the Highland Mountains, plot well within the volcanic-arc granite region of trace element variation diagrams after Pearce et al. (1984). Potassic gneisses of the Tobacco Root Mountains, like those from Alder Gulch and the Greenhorn Range, plot near the junction of volcanic arc granite, syncollisional granite, and within plate granite.

Low $K_2O/Na_2O$ ratios are characteristic of I-type granites that form in volcanic arc settings. High $K_2O/Na_2O$ ratios can indicate an S-type granite protolith that received significant input from anatexis of continental crust. The distinction between sodic and potassic gneisses in the Highland Mountains and the Greenhorn Range/ Alder Gulch may reflect protolith formation in different regions of the volcanic arc complex or at different stages in development, as the active arc gave way to continental collision. Isotopic analyses (initial $^{87}Sr/^{86}Sr$ and Sm-Nd ratios) could be used to test this hypothesis as well as resolve chronology.

The mobility of alkalis, however, undermines their value in characterizing protolith and tectonic setting. Mogk interprets discrepancies in $K_2O/Na_2O$ ratios of felsic gneisses of the Tobacco Root Mountains to reflect potassic alteration that may have occurred long after protolith formation, perhaps during emplacement of hydrothermal mineral deposits associated with Tertiary granitic plutons. REE patterns, which are relatively immobile and thus more reliable indicators of tectonic setting, are similar within the felsic gneisses of each study area and perhaps reflect the same igneous protolith. Mogk and others (2004) therefore draw no distinction between the igneous protoliths of the felsic gneisses

Spider diagrams were used to further determine magmatic affinities of gneisses in the Tobacco Root Mountains. Felsic gneisses are generally enriched in LILEs and depleted in Nb and P (Mogk et al., 2004). This pattern, also present in gneisses of the current study, has been interpreted as a signature for rocks from volcanic arcs (Davidson, 1996). Based on geochemical data and field evidence, Mogk and others interpret the gneisses of the Tobacco Root Mountains to have originated in an active continental margin, most likely in a backarc setting rather than along an arc axis. This interpretation is consistent with the results of the current study.

# CONCLUSIONS

Quartzofeldspathic gneisses of the Highland Mountains, Greenhorn Range, and Alder Gulch are metamorphosed rhyolites and dacites. Geochemical data indicate that the protoliths, along with associated mafic magmas, were extruded in the back-arc region of a subduction zone complex. This interpretation concurs with Mogk and others' (2004) characterization of the protolith and tectonic setting of quartzofeldspathic gneisses in the Tobacco Root Mountains.

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