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GEOCHEMISTRY OF ARCHEAN (?) AMPHIBOLITES IN SOUTHWESTERN MONTANA

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INTRODUCTION

Metamorphosed mafic rocks that form the basis of this Keck project are found throughout Precambrian exposures in southwestern Montana (Mogk et al., 1992; Burger, 2004; Harms et al., 2004). The purpose of this study is to examine the mineralogy and whole-rock geochemistry of these mafic rocks in order to determine their protoliths and the geologic setting in which they originally were formed.

Samples of metamorphosed mafic rocks were collected from four regions in which Archean (?) rocks are exposed. Whole rock geochemical analysis was performed using the inductively coupled argon plasma spectrometer at Middlebury College to determine major and selected trace element concentrations. A full suite of trace elements, including rare earths, were analyzed by Acme Labs in British Columbia.

DESCRIPTIONS OF AMPHIBOLITE BODIES

In the Greenhorn and Highland Ranges, amphibolite bodies occur within suites of quartzofeldspathic gneiss as lenses or layers that mimic the smaller scale compositional banding of the gneiss bodies. The layers and lenses are typically 0.5 to 10 meters thick, and can be up to 100 meters in length. Fine-grained metabasalts occur as small outcrops (1-5 meter exposures) within the metasupracrustal rocks of the central Gravelly Range as well. In the southern Gravelly Range, regionally metamorphosed mafic intrusions into metasupracrustal rocks take the form of small plutons, sills, and dikes that range from 5 to 120 meters across.

The amphibolites of the Greenhorn Range are similar to those contained within the large bodies of quartzofeldspathic gneiss that comprise the bulk of the Indian Creek and Pony-Middle Mountain metamorphic suites in the Tobacco Root Mountains (Mogk et al., 2004). They are coarse-grained and contain primarily amphibole and plagioclase in subequal proportions, with lesser amounts of garnet, orthopyroxene, clinopyroxene, quartz, biotite, and apatite in some samples (Fig. 1). Most samples show foliation defined by gneissic banding of felsic and mafic minerals, and in some samples the amphibole occurs as needle-like grains in a preferred orientation.

The amphibolites of the Highland Range are subdivided based on the mapped gneiss units (O'Neill et al., 1994) in which they occur. Amphibolites from unit Xag are fine to medium grained, and show poorly to well-developed foliation defined by elongate amphibole grains. Mineralogy is dominated by amphibole; other minerals include plagioclase, which in most cases has been altered to epidote, subrounded garnets, quartz, apatite, and opaque minerals including chromite (Fig. 1). Amphibolites from Unit Xam are similar in mineralogy to those in Xag, but in places show strong light-colored

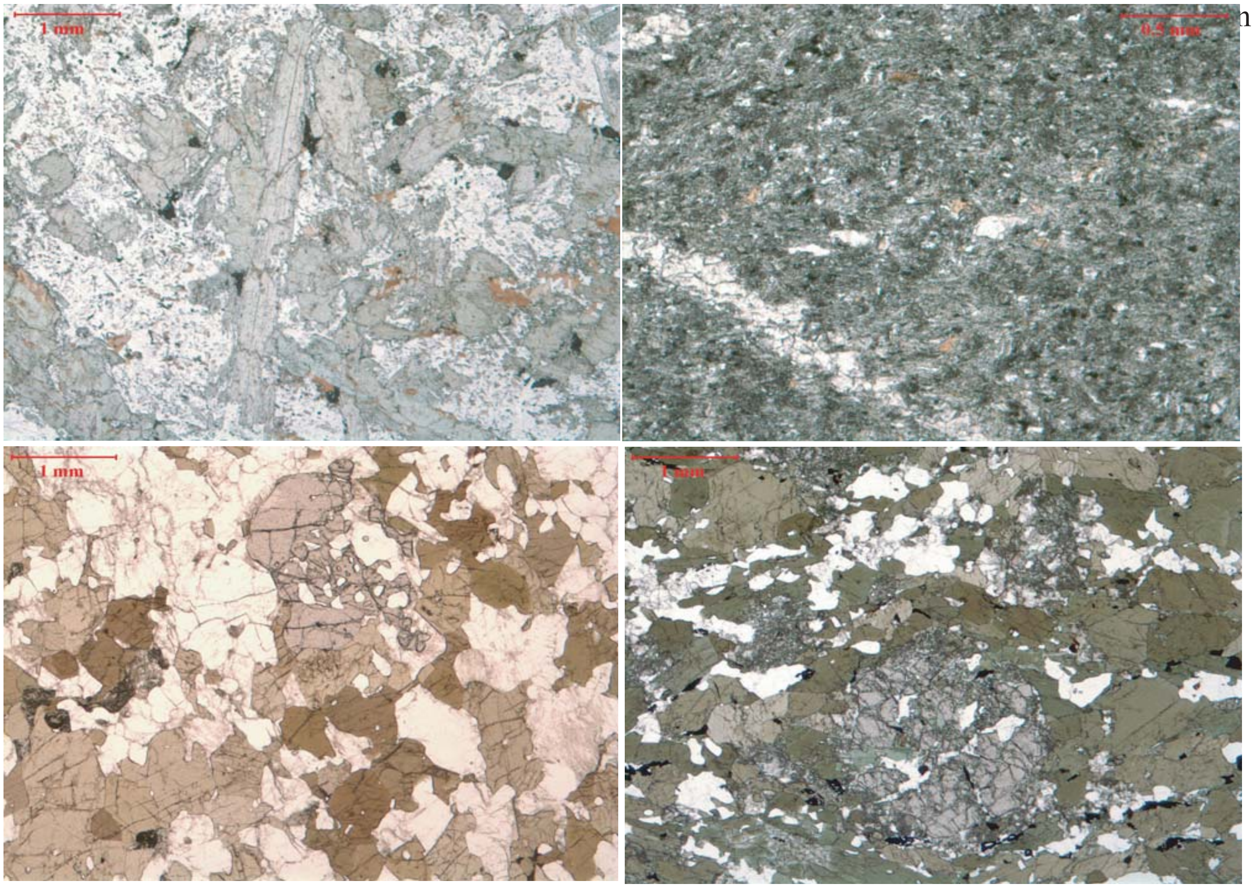

Figure 1 Photomicrographs in plane light of sample thin sections from (clockwise from top left): southern Gravelly Range (ESS-09), central Gravelly Range (ESS-24), Highland Range (ESS-29C), and Greenhorn Range (ESS-22).

bands consisting of unaltered plagioclase and quartz. The amphibolites from Unit Xaqf generally show a higher degree of alteration to epidote than those in the other two units, with little or no plagioclase remaining. They also tend to have significant amounts of opaque minerals, including chromite and ilmenite. The grain size and mineralogy of these rocks also varies within the unit, with samples containing varying amounts of epidote, quartz, garnet, serpentine and plagioclase. Overall, the amphibolites in Unit Xaqf show better developed foliation than those in the other two units, with many samples displaying gneissic banding of light and dark minerals, and/or consistent alignment of elongate amphibole grains.

The fine-grained metabasalts contained within the central Gravelly Range stand out from the metasupracrustal rocks that surround them foliation. These rocks contain mostly elongate amphibole grains and epidote, which likely formed as a replacement mineral for plagioclase (Fig. 1). Lesser amounts of plagioclase and biotite are also found in most samples. The rocks display some slight foliation or cleavage on an outcrop scale, but also preserve characteristics of igneous rocks, including radiating amphibole grains in thin section, and pillow forms at one large outcrop.

Medium-grained gabbro intrusions in the southern Gravelly Range are made up mainly of amphibole and plagioclase, with some biotite (Fig. 1). The rocks also include small amounts of epidote and calcite, which probably formed as alteration products. Some of these bodies are massive, whereas others show weak foliation in sections containing greater amounts of biotite. The edges of these intrusive bodies display chill margins, and in places the country rocks show evidence of contact metamorphism (see Doody, this volume).

GEOCHEMISTRY

All samples have SiO_2 content between 43 and 55 weight percent (Table 1), and plot within the basalt or basaltic-andesite fields on a silica vs. total alkalis classification diagram. Furthermore, on a Nb/Y vs. Zr/TiO_2 classification diagram, all samples plot within the subalkaline basalt field, except for a few which spill over into the andesite field (Fig. 2), and in AFM diagrams, samples for all four regions plot along a tholeiitic trend. Other major element concentrations are typical for rocks of basaltic composition for most samples.

On chondrite-normalized rare earth element (REE) diagrams (Nakamura, 1974), most of the samples from the Greenhorn Range are enriched in light REE (LREE) relative to heavy REE (HREE), which show a fairly flat pattern, and display a negative Eu anomaly. Conversely, three samples from the Greenhorn Range have fairly flat REE diagrams with no appreciable Eu anomaly. Samples from the central Gravelly Range and southern Gravelly Range are also enriched in LREE relative to HREE with a negative slope in the LREE and flat slope in the HREE, but none of these samples show any Eu anomaly. Samples from the Xag and Xam units of the Highland Range display a relatively flat slope on REE element plots with a slight enrichment in LREE and no Eu anomaly, but are much flatter than those from the other regions. REE plots from Highland unit Xaqf are slightly enriched in LREE relative to HREE , but show a wide spread between samples in their enrichment relative to chondrite, and no Eu anomaly.

Trace elements compositions of samples from the Greenhorn Range plotted on spider diagrams (normalized to N-MORB, Hoffman, 1988) show a significant negative Nb-Ta anomaly for all samples, with relatively flat patterns in the high field strength elements (HFSE) and a slight negative Ti anomaly in most samples (Fig. 3). Samples from the central Gravelly Range and southern Gravelly Range show similar patterns, with strong negative Nb-Ta anomalies in all samples (Fig. 3). Samples from Highland Range units Xag and Xam also show negative Nb-Ta anomalies on this spider diagram, although the anomalies are not as large as in samples from the Greenhorn Range, central Gravelly Range, or southern Gravelly Range; furthermore, these samples do not show negative Ti anomalies (Fig. 3). Samples from Highland unit Xaqf show a slight negative Nb-Ta anomaly on the spider diagram, and a flat pattern in the HFSE. As in REE plots, samples from this Highland unit exhibit a wide spread in their trace-element compositions relative to N-MORB (Fig. 3).

All samples were plotted on discriminant diagrams that use trace elements immobile during metamorphism. The samples from

	Southern Gravelly Range		Central Gravelly Range			Greenhorn Range		Highlands Xag	Highlands Xam	Highlands Xaqf
	ESS-02C	ESS-09	ESS-08	ESS-25	ESS-15	ESS-21	ESS-33B	ESS-30	ESS-12	ESS-06
SiO2	49.12	51.87	52.17	54.11	52.33	49.79	50.08	48.81	48.65	51.05
TiO2	0.99	0.51	0.79	1.03	0.49	0.90	1.54	1.60	1.88	1.47
Al2O3	17.05	16.35	14.35	14.37	11.10	14.51	15.28	13.61	15.01	13.60
Fe2O3(t)	9.31	8.22	10.69	11.40	11.14	14.35	14.13	14.41	15.38	15.28
MnO	0.14	0.13	0.21	0.14	0.16	0.22	0.13	0.23	0.23	0.29
MgO	9.16	6.73	7.06	6.38	10.19	6.62	6.33	6.61	7.30	5.93
CaO	10.52	10.67	11.76	7.47	12.09	9.28	8.46	10.95	12.08	9.43
Na2O	2.89	2.56	1.56	3.06	1.81	2.77	2.93	2.43	1.68	2.42
K2O	0.12	0.66	0.28	0.82	0.57	0.99	1.23	0.49	0.46	0.64
P2O5	0.17	0.05	0.08	0.11	0.03	0.08	0.17	0.13	0.15	0.13
Total	99.48	97.76	98.94	98.88	99.89	99.50	100.27	99.27	102.82	100.24

Table 1 Major element whole-rock geochemistry for selected samples.

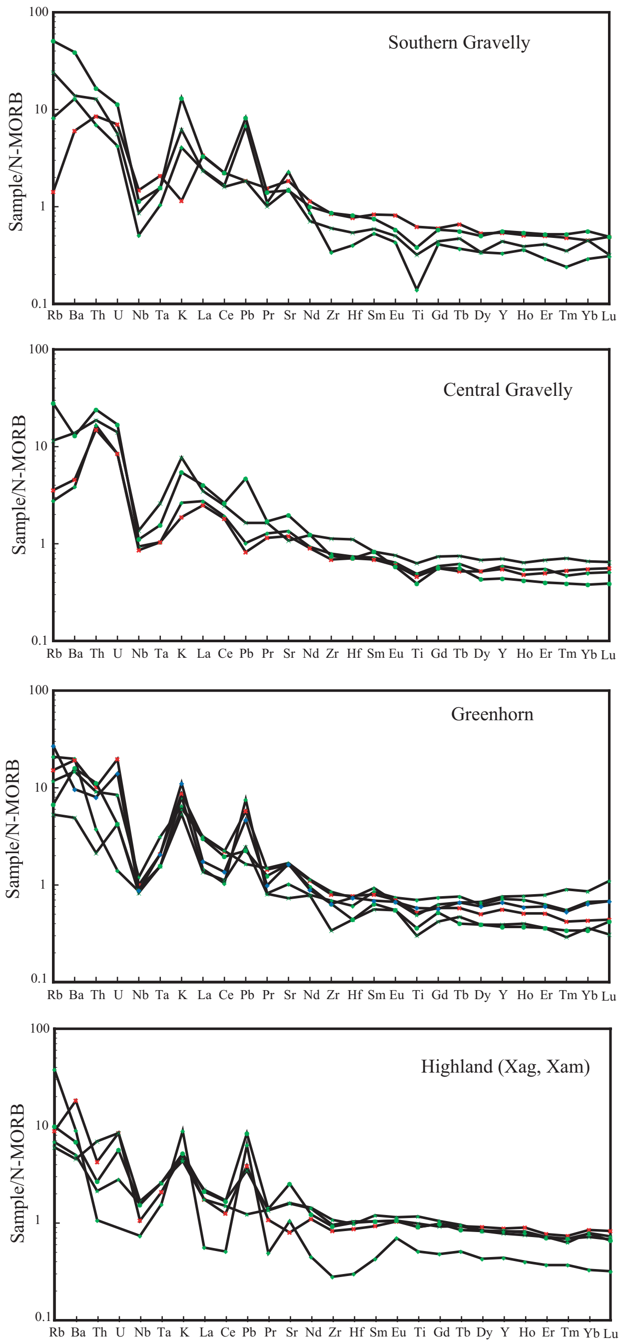

Figure 3 Spider diagrams of samples from the four study areas. The negative Nb-Ta anomalies in all regions is consistent with formation in volcanic arcs.

the Greenhorn Range plot primarily within volcanic arc or island arc tholeiite (IAT) fields on Nb-Zr-Y (Fig. 4A, after Meschede, 1986), Y-Cr, and Ti-Zr diagrams, with some samples plotting within MORB fields. Samples from the southern Gravelly Range plot entirely within volcanic arc fields on Hf-Th-Ta and Y-Cr diagrams, and show continental crust influence in subduction-related melts on a Ta/Yb-Ta/Yb diagram (Fig. 4B, after Pearce, 1983). Central Gravelly Range samples plot exclusively within IAT or volcanic arc fields on Ti-Zr, Y-Cr, and Hf-Th-Ta diagrams (Fig. 4C, after Thompson et al., 1980). Samples from within Highland units Xag and Xam plot primarily in MORB fields on Nb-Zr-Y, Ti-Zr-Y, and Ti-Zr diagrams, with one sample plotting in volcanic arc or IAT fields on these diagrams. Samples from these units also plot in a tight scatter around the back-arc basin basalt (BABB) field on the Y-La-Nb diagram and completely within the BABB/MORB field on the Ti-V diagram (Fig. 4D, after Shervais, 1982). Samples from Highland unit Xaqf show significant scatter, but tend to plot around MORB and volcanic arc fields on the diagrams listed above.

DISCUSSION

Based on the patterns displayed by REE and spider diagrams, it is likely that the metamorphosed mafic rocks of the southern Gravelly Range and central Gravelly Range were originaly formed in volcanic arc environments. Mafic rocks from the Greenhorn Range also show volcanic arc signatures, particularly the Nb anomaly in spider diagrams (Floyd and Winchester, 1978), but there may be more than one type of arc source that formed these rocks, as indicated by variations in where they plot on REE and discriminant diagrams. The amphibolites contained within Highland units Xag and Xam also display the negative Nb anomaly characteristic of volcanic arcs, but have REE plots and discriminant diagrams that are indicative of spreading-center basalts. One possible interpretation is that these rocks formed as part of back arc basin volcanism. It is difficult to pin down the environment in which the mafic rocks within Highland unit Xaqf formed since the samples from this unit are variable. ESS-05 has an ultramafic geochemical

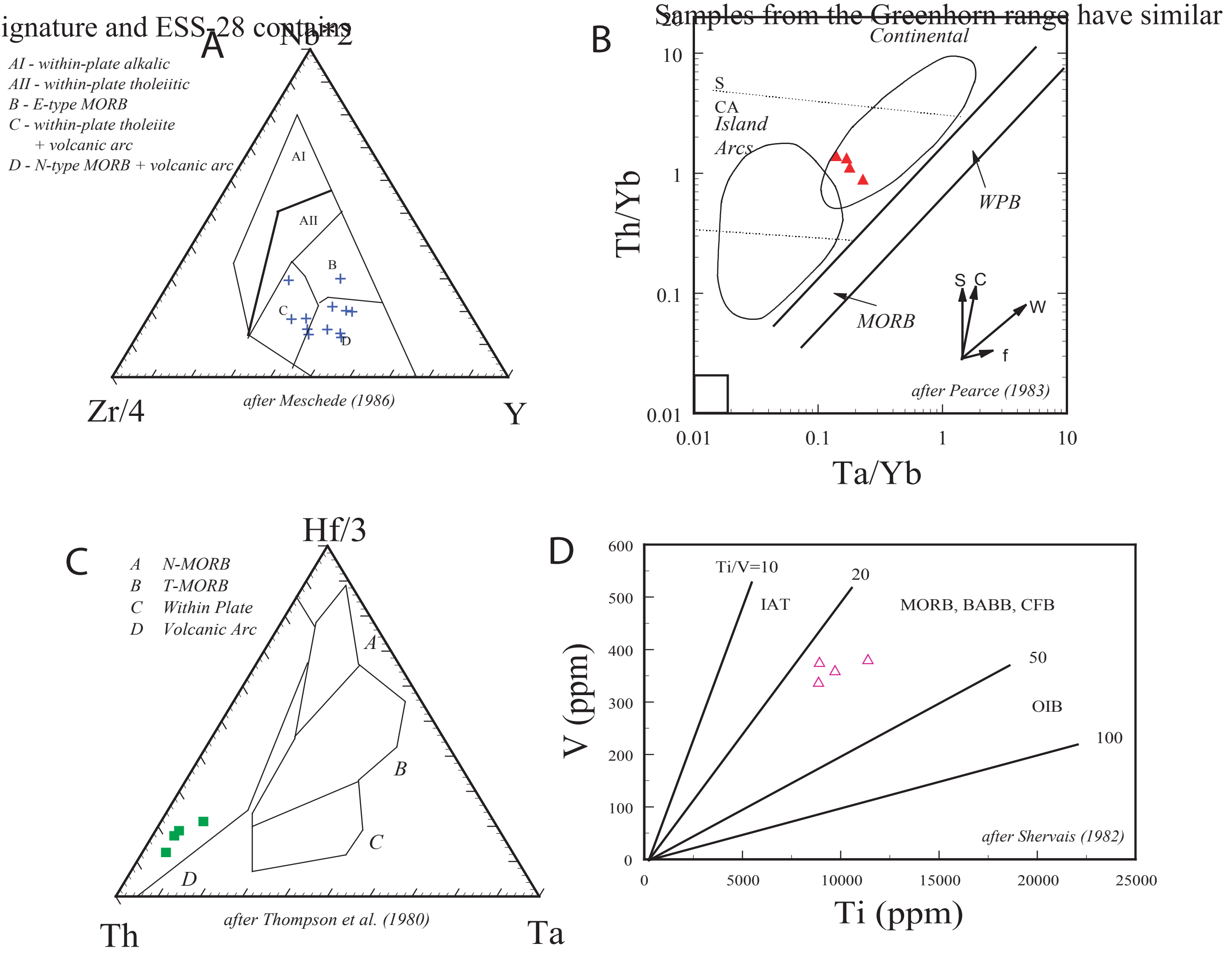

Figure 4 (A) Nb-Zr-Y discriminant diagram with all analyzed samples from the Greenhorn Range plotted. (B) Ta/Yb-Ta/Yb diagram with all samples from the southern Gravelly Range plotted. (C) Hf-Th-Ta diagram with all samples from the central Gravelly Range plotted. (D) Ti-V diagram with samples from Highland Range units Xag and Xam plotted.

signature and ESS-28 contains significant quartz, and could have a sedimentary protolith. Other samples have both volcanic arc and spreading-center affinities, depending on the diagram used. Until more extensive sampling of mafic rocks in this unit can be done, no further conclusions can be drawn regarding their origin. Geochemical analyses of quartzofeldspathic gneisses in the Greenhorn and Highland Ranges also show volcanic arc signatures (see Fertig, this volume), and probably formed in the same tectonic setting.

Samples from the Greenhorn range have similar mineralogies, REE patterns, and Nb anomalies in spider diagrams to metamorphosed mafic rocks from the Tobacco Root Mountains, and potentially formed during the same tectonic event, based on these similarities and their geographic proximity. Because of differences in mineralogy and chemistry, metamorphosed mafic rocks from the southern Gravelly Range and central Gravelly Range are probably unrelated to those found in the Tobacco Root Mountains, including the metamorphosed mafic dikes and sills.

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