

GEOCHEMISTRY OF METAMORPHOSED PROTEROZOIC(?) MAFIC DIKES AND SILLS, HIGHLAND MOUNTAINS, MONTANA

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INTRODUCTION

The Highland Mountains of southwest Montana lie north of the Ruby Range and west of the Tobacco Root Mountains in the Wyoming province of North America. The Precambrian metamorphic basement rocks of the Highland Mountains have been folded into a doubly plunging antiform that trends northeast to east and forms the Highland Mountains dome (O'Neill et al., 1988). O'Neill et al. (1988) classify the Precambrian rocks into five map units: three principal gneisses, a suite of igneous rocks, and well-layered amphibolite. The igneous suite is composed of metabasite dikes and sills (MMDS), aplite and granitic pegmatite sills and minor dikes, and diabase dikes. According to O'Neill et al. (1988), "... a preliminary U-Pb zircon geochronologic study of the crystalline basement rocks of the Highland Mountains document a major 1.8 Ga penetrative metamorphic event." Robertson (2000) concludes that the basement rocks reached the first sillimanite isograd of amphibolite grade metamorphism. This study looks at the metamorphosed mafic dikes and sills (O'Neill et al.'s metabasites) of the Highland Mountains.

MMDS in the Tobacco Root Mountains that intrude and crosscut 2.45 Ga foliation at 2.06 Ga have been geochemically analyzed (Brady et al, 2004). $^{40}\text{Ar}/^{39}\text{Ar}$ dating of amphibole indicates that the MMDS and the rocks they intrude subsequently underwent an upper-amphibolite

to lower-granulite facies metamorphism at 1.78 to 1.71 Ga in an event that has been named the Big Sky orogeny (Harms et al., 2003). Similar cross cutting of gneiss, weathering patterns, and mineralogy of the Highland Mountains and Tobacco Root Mountains MMDS pose the question of whether these MMDS are related, and if so, in what ways. This study investigates the following specific questions. (1) What are the chemical compositions of the Highland Mountains MMDS? (2) What do these compositions reveal about the tectonic setting during the intrusion of the MMDS? and (3) Is there a common source for the MMDS of the Highland Mountains and the Tobacco Root Mountains?

FIELD RELATIONS

O'Neill et al. (1988) describe the MMDS in the Highland Mountains as weakly foliated, dark brown to black dikes and sills primarily composed of hornblende, garnet, augite, and plagioclase that range in thickness from less than 1 meter to 10-15 meters. Most samples used for this study come from extensively fractured, blocky, low outcrops less than five meters in thickness and trending northeast. The MMDS intrude and crosscut the layering of the surrounding gneisses, leaving a sharp boundary in at least one instance and indicating that the metamorphism that caused the gneissic banding predates the intrusion of the MMDS into cold rocks. Several dikes exhibit their own foliation and most contain

garnet. These two observations demonstrate that the metamorphism of the MMDS postdates the first metamorphism of the gneisses. The presence of garnet in a sample was particularly important in distinguishing a thin MMDS from mafic compositional layering in the host gneiss where the sample did not truncate the gneissic layering. Cross cutting of the MMDS by granitic dikes was clear at two sites, but these MMDS were not foliated and so it is not possible to say whether the granites intruded before or after the metamorphism.

METHODS

Seventeen samples from fourteen locations were analyzed for whole-rock chemistry (Table 1). The samples were chosen to represent the broadest geographic distribution, minimal weathering, and the presence of garnet. Major elements were measured on fused La-bearing lithium borate glass discs and trace elements were measured on powder pellets using x-ray fluorescence analysis (XRF) on a Siemens SRS-1 sequential spectrometer. All chemical analyses were obtained using equipment at the University of Massachusetts at Amherst and analytical techniques are described in Rhodes (1996). All chemical analyses are reported on an anhydrous basis. Fe_2O_3 content was measured, but the results have been converted and are reported as weight percent FeO. One major element analysis for SJM-08b produced lower weight percentages for most major oxides and a significantly lower SiO_2 wt%. This is likely attributed to a weighing error during preparation for the XRF. Because this analysis is anomalous, the data can be found in Table 1 but will not be included in the rest of the study. Sample SJM-12 has significantly lower SiO_2 , Zr, Y and more than twice the V as the sample with the next highest ppm of V probably as the result of later alteration. Therefore, sample SJM-12 will be considered anomalous for the rest of this study and will not be included in compositional ranges but will be represented in graphs and

indicated as anomalous.

RESULTS

Major element chemistry demonstrates a subalkaline tholeiitic protolith for the MMDS (Table 1: see last page of this paper; Fig. 1). SiO_2 ranges from 48.75 to 51.45 weight percent and the alkali sum $\text{Na}_2\text{O} + \text{K}_2\text{O}$ is less than or equal to 3% by weight. Fractional crystallization is evidenced by a $\text{Mg}/(\text{Mg} + \text{Fe})$ molar ratio range of 0.37 to 0.53 and a P_2O_5 range of 0.06 to 0.15 weight percent.

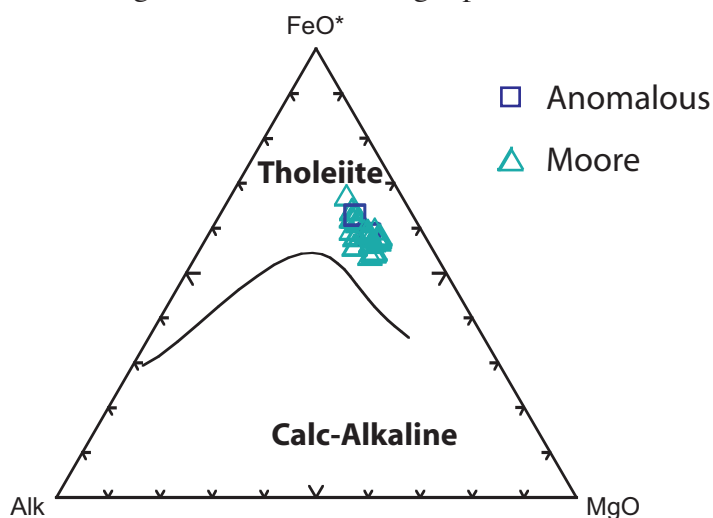


Figure 1. MMDS analysis of weight percent oxides as shown on Irvine and Baragar's (1971) AFM diagram. The data show that the MMDS are tholeiites that are becoming more Fe-rich as the alkalis remain constant. The range of Fe/Mg values are consistent with mineral fractionation.

Although the content of P_2O_5 and Zr each range by at least a factor of two, the ratio of P_2O_5 to Zr is virtually constant (Fig. 2) consistent with a common origin for all samples. If that is so, since both P_2O_5 and Zr vary by at least a factor of two, at least fifty percent of the liquid must have been crystallized between the first and last intrusion. The constant ratio of P_2O_5 to Zr also demonstrates that P_2O_5 and Zr are similarly incompatible with the fractionating minerals, and therefore P_2O_5 and Zr can be used as normalizing components. The molar ratio of $\text{Mg}/(\text{Mg} + \text{Fe})$ declines as the molar ratio of

Table 1.

Source	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE
Sample	SJM-01	SJM-02	SJM-04A	SJM-05	SJM-08B	SJM-08C	SJM-09A	SJM-09B	SJM-10B				
#Analyses	4	2	2	2	2	2	1	1	2	1	1	1	2
Host Rock	X(A)qf	X(A)qf	X(A)qf	X(A)qf	X(A)qf	X(A)qf	X(A)q	X(A)q	X(A)q	X(A)q	X(A)q	X(A)q	X(A)q
12T	389189	383547	385233	385346	396423	396423	397948	397948	397948	397948	397948	397948	394925
UTM	5048015	5050717	5054425	5054434	5060581	5060581	5056149	5056149	5056149	5056149	5056149	5056149	5058688
<u>Oxide (wt%)</u>													
SiO ₂	50.55	51.03	50.01	51.06	48.08	50.15	48.75	50.38	50.97	50.38	50.15	48.75	50.97
TiO ₂	0.90	0.91	1.23	1.25	1.22	1.18	1.93	1.02	1.65	1.02	1.18	1.93	1.65
Al ₂ O ₃	14.30	13.49	13.38	13.40	13.59	14.99	13.08	15.87	13.24	15.87	14.99	13.08	13.24
FeO	11.74	12.74	13.68	14.23	13.08	12.76	16.01	11.00	13.74	11.00	12.76	16.01	13.74
MnO	0.21	0.24	0.25	0.24	0.24	0.20	0.30	0.21	0.23	0.21	0.20	0.30	0.23
MgO	7.40	6.36	6.24	5.64	6.87	5.61	5.42	5.89	6.13	5.89	5.61	5.42	6.13
CaO	11.37	10.13	10.72	9.99	11.64	10.21	10.40	10.86	9.94	10.86	10.21	10.40	9.94
Na ₂ O	2.00	2.14	2.21	2.27	2.16	2.14	2.41	2.29	2.11	2.29	2.14	2.41	2.11
K ₂ O	0.60	0.83	0.32	0.29	0.16	0.60	0.20	0.64	0.37	0.64	0.60	0.20	0.37
P ₂ O ₅	0.08	0.07	0.09	0.10	0.08	0.12	0.13	0.10	0.14	0.10	0.12	0.13	0.14
Total	99.15	97.94	98.13	98.46	97.12	97.96	98.64	98.27	98.52	98.27	97.96	98.64	98.52
<u>Trace elements (ppm)</u>													
Nb	4.1	2.0	3.0	3.4	2.5	7.0	4.0	6.0	7.4	6.0	7.0	4.0	7.4
Zr	62	56	69	78	67	107	99	91	99	91	107	99	99
Y	20.9	21.8	27.1	28.1	24.7	26.9	34.1	22.7	25.1	22.7	26.9	34.1	25.1
Sr	133	119	90	75	76	139	82	136	185	136	139	82	185
U	1.0	1.0	1.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Rb	14.0	30.3	7.3	7.6	3.4	19.0	4.7	23.2	8.6	23.2	19.0	4.7	8.6
Th	2	1	1	1	1	2	1	2	1	2	2	1	1
Pb	3	4	2	2	1	4	1	4	2	4	4	1	2
Ga	15	16	18	19	19	18	21	18	18	18	18	21	18
Zn	105	113	110	129	101	112	122	99	129	99	112	122	129
Ni	101	51	50	42	80	84	44	84	78	84	84	44	78
Cr	206	58	83	79	123	155	64	188	100	188	155	64	100
V	280	312	354	372	347	259	448	241	367	241	259	448	367
Ce	10	12	12	12	7	25	14	20	20	20	25	14	20
Ba	152	171	100	133	89	389	90	212	205	212	389	90	205
La	3	0	4	6	0	8	2	6	2	6	8	2	2
Ti	0.89	0.87	1.11	1.20	1.20	1.16	1.94	1.06	1.50	1.06	1.16	1.94	1.50

Table 1, continued.

Source	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE	MOORE
Sample	SJM-10D	SJM-12	SJM-13A	SJM-14	SJM-15A	SJM-17	SJM-18	SJM-19
#Analyses	2	2	1	2	4	2	2	2
Host Rock	X(A)q	X(A)q	X(A)q	X(A)q	X(A)q	X(A)qf	X(A)qf	X(A)qf
12T	394925	395805	393104	387793	387980	386132	393650	393800
UTM	5058688	5059374	5061434	5053380	5059374	5054423	5061050	5061100
<u>Oxide (wt%)</u>								
SiO[2]	50.91	45.51	49.60	51.19	50.38	50.56	49.28	49.55
TiO[2]	1.69	1.12	1.33	1.01	1.00	0.97	1.28	1.27
Al[2]O[3]	13.30	14.64	13.54	12.95	14.27	13.83	13.52	13.35
FeO	13.86	14.68	13.48	12.49	12.38	12.25	13.32	13.19
MnO	0.23	0.21	0.26	0.22	0.22	0.23	0.25	0.25
MgO	5.93	6.07	6.86	7.39	7.17	7.07	6.93	7.07
CaO	9.97	11.11	11.15	11.26	11.29	11.27	11.37	11.99
Na[2]O	2.26	2.27	2.24	1.54	1.73	2.21	2.18	2.12
K[2]O	0.37	0.32	0.37	0.52	0.36	0.27	0.27	0.12
P[2]O[5]	0.15	0.03	0.09	0.09	0.09	0.06	0.09	0.09
Total	98.67	95.97	98.93	98.67	98.89	98.73	98.49	99.00
<u>Trace elements (ppm)</u>								
Nb	8.0	2.9	2.8	4.2	4.7	3.4	2.4	2.4
Zr	105	33	68	75	72	61	58	64
Y	25.8	14.0	25.3	25.0	24.3	21.6	22.4	24.9
Sr	121	92	133	118	120	120	109	86
U	1.0	1.0	1.0	1	1	1	1	1
Rb	7.7	2.7	6.9	13.8	13.6	8.8	5.5	3.3
Th	1	1	1	2	2	2	2	1
Pb	2	2	3	4	3	3	2	2
Ga	19	18	18	18	17	18	19	19
Zn	126	65	114	112	109	108	104	103
Ni	78	62	68	90	99	73	62	78
Cr	85	4	106	163	182	124	94	117
V	371	1016	364	338	288	293	334	364
Ce	24	13	3	12	16	13	10	8
Ba	150	96	210	213	408	272	49	23
La	2	2	0	3	5	2	1	1
Ti	1.60	1.15	1.26	1.14	0.99	0.94	1.02	1.20

MgO/P₂O₅ declines which is consistent with the incompatibility of P₂O₅ with the fractionating minerals.

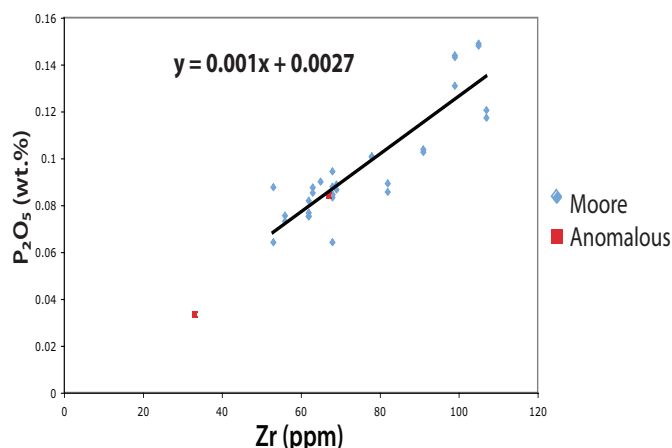


Figure 2. Weight percent P₂O₅ vs. weight percent Zr for the MMDS. These data are consistent with both P₂O₅ and Zr being largely incompatible with any fractionating minerals. The largest value of both P₂O₅ and Zr is twice the smallest value, indicating that as much as 50% of the original liquid was removed by fractional crystallization if there was a single magmatic source.

Olivine is commonly an early mineral to fractionate from a basaltic melt. However, in the Highland Mountains the data demonstrate that olivine is not a significant fractionating mineral for the MMDS. As the Mg# (MgO/(MgO + FeO)) decreases, there is a slight decrease in SiO₂. If olivine were a major fractionating phase, an increase in SiO₂ would follow the decrease in Mg#. Also, there is little correlation between the SiO₂ content and the P₂O₅ content whereas an increase in SiO₂ would accompany the increase in P₂O₅ if there were significant olivine removal. In addition a strong correlation between Ni and MgO would be expected if there was significant olivine fractionation, but the data reveal only the slightest compatibility. CaO, Al₂O₃, and MgO all decrease as Mg# decreases. The decrease in Al₂O₃ can be attributed to fractionation of plagioclase. The ratio of CaO to Al₂O₃ remains almost constant as Mg# decreases, indicating that clinopyroxene is probably not a significant

fractionating phase and that the decrease in MgO and Mg# can be explained by a low-Ca pyroxene fractionating phase. Combinations of fractionating phases of plagioclase, orthopyroxene, clinopyroxene and olivine were plotted (Fig. 3) using the procedures of Russell and Stanley (1990). The combination of plagioclase, orthopyroxene, and clinopyroxene plotted at a slope of 1.0 and is the best candidate for explanation of the variation of SiO₂/P₂O₅. This test does not rule out the fractionation of olivine or other phases consistent with the interpretation that olivine is not a significant fractionating mineral.

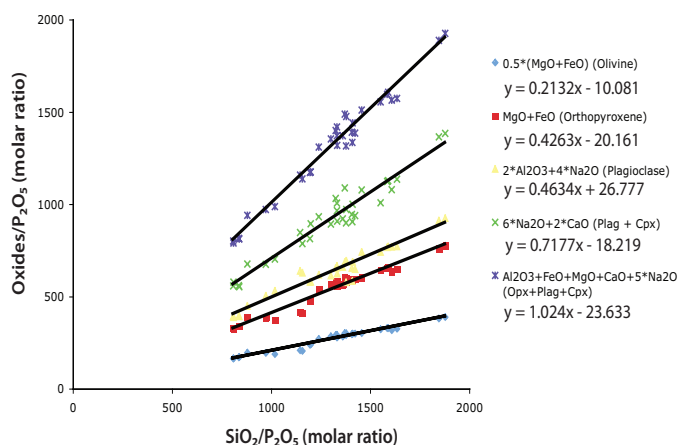


Figure 3. Pearce element ratio diagram showing several tests for fractional crystallization of Highland Mountains MMDS using P₂O₅ as a normalizing component. Combinations of fractionating phases were plotted using the procedures of Russell and Stanley (1990). The test for orthopyroxene, plagioclase and clinopyroxene has a slope of one, indicating that all of the variation of SiO₂/P₂O₅ can be explained by fractional crystallization of these minerals.

Most of the trace elements increase in parts per million as MgO decreases in weight percent probably because they are incompatible with the fractionating minerals (Winter, 2001). Several trace elements show less of an increasing trend with decreasing MgO than other elements that are less compatible with those minerals. Pb, V, and Zn essentially remain constant, which is consistent with fractionation of plagioclase and clinopyroxene, and orthopyroxene, respectively (Brady et al., 2004). However, Y is also

compatible with clinopyroxene and it shows a strong increasing trend no less significant than less compatible elements (Brady et al., 2004). Cr and Ni both have large coefficient constants for olivine and show slight decreases as MgO decreases and Cr varies by a factor of four or more.

DISCUSSION

The field relations of the MMDS relative to other rock units in the Highland Mountains allow us to come to important conclusions about the Highland Mountains. The basaltic protolith of the MMDS was a subalkaline tholeiite that intruded the quartzofeldspathic gneiss in the core of the dome and the overlying quartz-feldspar-biotite gneiss in the structurally higher part of the core of the dome. The chilled margins of at least one MMDS in the quartz-feldspar-biotite gneiss, suggest that the gneissic rocks had cooled post metamorphism and before the gneisses were intruded by the mafic dikes and sills. The cross cutting of gneisses by mafic dikes and sills indicates that the basalts were intruding a continental setting at either a rift or a hotspot. The cross cutting relations, geochemistry, and mineralogy of the Tobacco Roots MMDS are consistent with intrusion into a continental rift setting (Brady et al., 2004). Both the Highland Mountains and Tobacco Root Mountains tectonic settings must have remained in place long enough for significant crystal fractionation of the MMDS to take place. Compared to an oceanic tholeiite, the crystallization sequence of a continental tholeiite is more likely to contain orthopyroxene (Campbell, 1985), which is a significant fractionating phase in both the Highland Mountains and Tobacco Root Mountains MMDS. Crystal fractionation is best modeled by a combination of plagioclase, orthopyroxene, and clinopyroxene in both units while olivine was an insignificant phase. P_2O_5 and Zr were similarly incompatible for the MMDS in the Highland Mountains indicating that the MMDS

came from a common origin, of which 50 percent of the original liquid was removed. A plot of the weight percent of P_2O_5 versus the ppm of Zr (Fig. 4) for the available data from both the Tobacco Root Mountains and the Highland Mountains yields the same constant ratio (Brady et al, 2004).

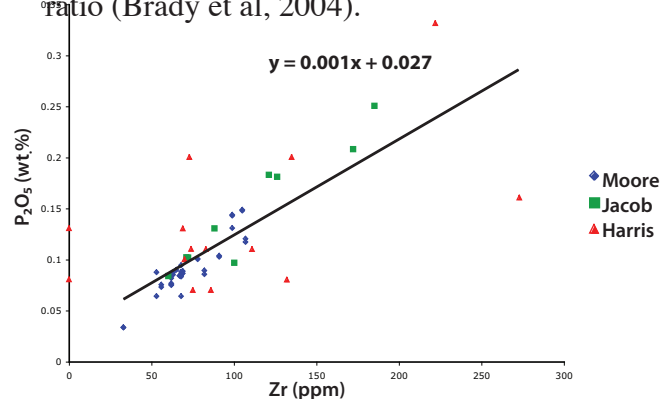


Figure 4. P_2O_5 shown as a function of Zr for the MMDS of the Highland Mountains (Moore) and the Tobacco Root Mountains (Jacob and Harris from Brady et al., 2004). Together, samples from both mountain ranges show the same trend of constant P_2O_5 content to Zr content, which would make them both largely incompatible with any fractionating minerals.

However, the data from the Tobacco Root Mountains for the MMDS consistently show a wider range than data from the Highland Mountains. Trends that otherwise did not appear in the Tobacco Root Mountains data become more plausible when the Highland Mountains data are added to a plot. For example, a plot of Ni vs. MgO for the Tobacco Root Mountains (Jacob and Harris) shows considerable scatter, but the addition of Highland Mountains data to the plot shows a decrease in MgO accompanied by a decrease in Ni for Jacob's data in the Tobacco Root Mountains and data from the Highland Mountains. This may be a statistical result that simply comes from having more data, however, it may suggest a relationship between the Highland Mountains MMDS and the Tobacco Root Mountains MMDS. Their proximity, similar field relations, and overlapping of some important chemical trends argue for a similar tectonic setting and age.

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