PETROGENESIS AND TECTONIC IMPLICATIONS OF MAFIC ROCKS IN THE PRECAMBRIAN CORE OF THE BLACK HILLS, SOUTH DAKOTA

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Master of Science

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by

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We the undersigned, appointed by the Dean of the Graduate School, University of Missouri-Columbia, have examined the thesis entitled:

PETROGENESIS AND TECTONIC IMPLICATIONS OF MAFIC ROCKS IN THE PRECAMBRIAN CORE OF THE BLACK HILLS, SOUTH DAKOTA

Presented by Angela Van Boening

A candidate for the degree of Master of Science

And hereby certify that in our opinion it is worthy of acceptance

Dr. Peter I. Nabelek

Dr. Robert L. Bauer

Dr. Timothy E. Glass

For Pastor Jim Polanzke –

Were it not for you, I may have never learned to appreciate creation.

“Speak to the earth, and it will teach you.”

Book of Job

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ABSTRACT

The Precambrian core of the Black Hills of South Dakota records evidence of the metamorphic, structural, and magmatic events that occurred in the area during the Proterozoic collision of the Wyoming and Superior provinces. While these syncollisional events are well understood, the geologic setting and tectonic events that occurred prior to the collision are still enigmatic. In this investigation petrography and geochemistry of four suites of amphibolites were used to define the mantle source and tectonic setting of the mafic suites in the Black Hills prior to the collision.

Major and trace element ICP-OES and INAA data were used to define at least two distinct tectonic settings of mafic magmatism within the Black Hills. The Blue Draw Metagabbro (BDM) located on the eastern edge of the Black Hills' Precambrian core is the largest single mafic body in the Black Hills, and has been dated at 2.48 Ga. Previously, the BDM was thought to be a rift-related sequence, however, the geochemistry of the BDM shows a distinct calc-alkaline affinity, not unlike the slightly older Little Elk Granite that occurs in the vicinity. The geochemical characteristics of these rocks suggest a continental arc setting related to a subduction zone.

The amphibolites in the three other areas of the Black Hills have a tholeiitic affinity. The amphibolites at Minnesota Ridge have a distinctive within-plate geochemical signature; however they are depleted in Ba and Y, and enriched in LREEs, which may indicate a lithospheric, garnet-bearing mantle source associated with the initiation of a spreading center. The remainder of the amphibolites in the Black Hills, located in the Mt. Rushmore and Pactola Dam quadrangles, and near Bear Mountain have MORB to island arc tholeiitic compositions. These characteristics, together with the sedimentary environment in which they occur, suggest spreading center, probably at a back-arc basin tectonic setting.

The geochemical characteristics of the amphibolites suggest at least two distinct pre-collisional tectonic environments which were then juxtaposed during collision of the Wyoming and Superior cratons. This new evidence presents at least one distinctly new tectonic implication for the pre-collisional history of the Black Hills.

1 Introduction

The Precambrian core of the Black Hills of South Dakota has for some time been interpreted as the southernmost extent of the Proterozoic Trans-Hudson Orogen (TH orogen). Until recently, the majority of the work done on the Precambrian core of the Black Hills has focused on processes that occurred during the collision of the Wyoming and Superior cratons, including deformation, metamorphism and magmatism. In fact, it has recently been suggested that this collision was a separate event from the TH orogeny that occurred in Canada, and has been named the Black Hills orogeny (BH orogeny; Chamberlain et al. 2003). The campaign to understand these collisional events has left the pre-collisional history of the area relatively neglected. Most of the Precambrian rocks in the Black Hills predate the Wyoming-Superior collision, and while most of the now metamorphosed sedimentary rocks and Archean granites have been well-documented (Gosselin et al. 1988; Redden et al. 1990; McCombs et al. 2004), the petrogenesis of mafic dikes and sills that occur throughout the entire Precambrian core remains poorly understood. The focus of this study is on the petrology and geochemistry of these mafic units in order to assess their petrogenetic environments, and thus the pre-collisional tectonic history of the Black Hills.

Understanding the tectonic nature of the Black Hills prior to the BH orogeny has proven to be problematic. The orogenic deformation and metamorphic events that overprinted the precollisional characteristics of the terrain make it difficult to interpret the preceding geologic history. Archean granite plutons and the nature of sedimentation that occurred in the Black Hills have until now served as the basis for much of the tectonic interpretations. The Archean plutons include the Bear Mountain granite (BMG), which occurs on the west margin of the Precambrian terrain, and Little Elk (LEG) granite, which occurs on the east margin. The two tectonic models that seem to account for both the presence of the BMG and LEG and the sedimentary sequences were developed by Karlstrom and Houston (1984) and by Redden et al. (1990). Karlstrom and Houston (1984) suggested that an Archean block collided with the Wyoming Province and was later rifted to form the metasedimentary units. Redden et al. (1990) proposed that there were two periods of rifting that exposed the LEG and the BMG, and formed the basin in which the sedimentary sequences were deposited. Both of these models suggest that the sedimentary sequences adjacent to each of the granites are from the same rifting event, and therefore correlative. The justifications for this assumption are apparent stratigraphic correlations between the metasedimentary units across the Black Hills. Some workers have questioned the wisdom of correlating the metasedimentary units across the Black Hills (Noble and Harder 1948, Ratte and Wayland 1969, Hill 2006), as the terrain has been subjected to a complex deformational and thermal history which includes multiple folding and faulting events, metamorphism, as well as the intrusion of the late-orogenic Harney Peak Granite. The basis for the stratigraphic correlations extends from various textural and petrologic similarities, however little age data are available for these sequences. Most are derived from limited dates on intervening tuffs (Redden et al. 1990). Though the metasedimentary sequences appear similar in nature, no marker beds or direct depositional ages exist to definitively correlate units at Bear Mountain to units near the Little Elk granite.

Aggressive correlation of these sequences without marker beds raises concerns for two reasons. The first reason is that these units have been thoroughly deformed. There have been at least three Proterozoic deformational events in the Black Hills (Redden et al. 1990). Multiple folding and faulting are well documented from traceable faults and from fabric within the metamorphic rocks. The second reason for concern is that the Bear Mountain and the Little Elk terranes are separated by several major NNW trending faults.

Though the stratigraphic correlations are not an intrinsic part of this study, the presumed tectonic environment for their formation is. Both of the proposed models include deposition during epicratonic rifting based upon the presence of turbidite and pelitic sediments which would likely be found at a marginal marine environment. The numerous amphibolites have been interpreted to be rift-related flows based on their association with the sediments. It is interesting, however, that while the sequences in the Black Hills have been interpreted to be rift-related, while much of the TH orogeny in Canada has been interpreted as an amalgamation of juvenile arc-related Paleoproterozoic terranes, deformed marginal deposits, and ophiolite sequences (Bickford et al. 1990). Prior to this study, there have been no verifications of the epicratonic rifting models from the petrology and geochemistry of mafic rocks.

Although most of the amphibolites in the Black Hills have not been directly dated, they are correlative with the pre-BH orogeny sedimentation. The Blue Draw Metagabbro (BDM) however is substantially older. Until recently, the BDM was thought to be 2170 Ma (Redden et al. 1990), but Dahl et al. (2003) obtained a U-Pb age of 2480, making the BDM 310 Ma older than previously thought. With this older age, Dahl et al. (2006) proposed that the BDM may be a potential link in the pre-2480 Ma reconstruction of Kenorland, a late Neoarchean assembly of the Wyoming and Superior provinces (Roscoe and Card 1993). Dahl et al. (2006) suggest that the BDM is part of a rift-related sequence associated with the break up of Kenorland between 2480 and 2450 Ma.

Little has been done beyond field observations and relationships to determine the tectonic environment for the formation of the mafic suites within the Black Hills. It is therefore the objective of this study to compare and contrast four distinctive suites of amphibolites across the Black Hills to discern the range of tectonic environments in which the original mafic flows and intrusions formed, and hence to elucidate the pre-collisional geologic history of the Black Hills.

2 Geologic History

2.1 General Background

The Precambrian core of the Black Hills forms a large oblong dome which is flanked by Phanerozoic sedimentary rocks on all sides. The Black Hills were uplifted during the Laramide orogeny, and subsequently exhumed to their present day elevation during the Eocene (Redden et al. 1990). The majority of the Precambrian rocks exposed are Proterozoic metasedimentary and metavolcanic units. There are, however, three notable granitic bodies within the core, as well as several mafic dikes and sills (Figure 2.1). Of the granitic bodies, the oldest is the Bear Mountain granite, dated at 2596 ± 11 Ma, followed by the Little Elk granite at 2559 ± 6 Ma (McCombs et al. 2004), and the considerably younger Harney Peak granite at 1715 ± 3 Ma (Redden et al. 1990).

In addition to the granitic bodies, there are several mafic units that are scattered throughout the Hills. These are relatively small outcrops, few of which have adequate age constraints. The largest of these mafic bodies is the Blue Draw Metagabbro, located near the town of Nemo. Sphenes from the Blue Draw have an average age of 2482 ± 9 Ma (Dahl et al. 2003). The smaller mafic outcrops are considerably younger at approximately 1.88 Ga (Redden et al. 1990); however, most of these dates are constrained ages of the adjacent tuffs.

2.2 Granitic Units

The Bear Mountain granite (BMG) and associated terrane lie 21 km west of Hill City, SD and form the core of a structural dome which covers approximately 3 km^2. The BMG is a medium-grained to pegmatitic leucogranite with moderate to massive foliations. The BMG intrudes well-foliated biotite-plagioclase schist by small sills of either granite or trondhjemite. The granite is composed of quartz, plagioclase (An_{2-11}), microcline, and muscovite, with accessory apatite, biotite, and garnet. The trondhjemite is composed of quartz, plagioclase (An_{4-11}), muscovite, trace microcline, and accessory apatite and garnet (Gosselin et al. 1988).

Zircons from the BMG have been analyzed and yield a $^{207}Pb/^{206}Pb$ age of 2593 ± 20 Ma, and in situ SHRIMP analysis of several of the zircons give an age of 2592 ± 10 Ma, making the BMG the oldest terrane in the Black Hills. This age is interpreted to be the age of magmatic emplacement (McCombs et al. 2004). This also provides a minimum age of the schists in the Bear Mountain terrane that the BMG intrudes. McCombs et al. (2004) suggest two alternative models for petrogenesis of the BMG – as a melt associated with an accretionary wedge resulting from subduction of crustal material during continent-continent collision, or as juvenile material added to the terrain by vertical addition of mantle-derived melts during the Neoarchean to form granitic batholiths. Gosselin et al. (1988) suggest that the peraluminous characteristics of the BMG indicate that it was formed as a result of melting pelitic sediments in a regional metamorphism setting associated with continent-continent collision.

Associated with the Bear Mountain terrane is the Proterozoic Vanderlehr Formation – a locally derived marginal marine deposit of basal conglomerates, arkoses, and quartzites that unconformably overlies the Archean igneous and metamorphic rocks. Within the Vanderlehr are also several metabasalts, which will later be described in more detail.

The Little Elk Granite (LEG) is located in the far northeastern corner of the Precambrian core, about three miles north-northwest of the town of Nemo. The LEG ranges from a coarse-grained peraluminous to metaluminous porphyritic granite that is composed of quartz, microcline megacrysts, and biotite, with accessory muscovite, sphene, apatite, epidote, allanite, zircon, calcite, and opaques (McCombs et al. 2004). It exhibits a calc-alkaline affinity and has an isotopic signature that suggests a continental arc setting. U-Pb ages of the LEG have been calculated from zircons and indicate a magmatic origin ranging from 2559 ± 6 Ma (McCombs et al. 2004) to 2549 ± 11 Ma (Gosselin et al. 1988). Chamberlain et al. (2003) associates the LEG with a period of arc magmatism in the Wyoming province between 2.55 and 2.50 Ga.

Northwest of the LEG lies a biotite-feldspar gneiss (BFG). The BFG is a moderately to well-foliated, fine- to medium-grained gneiss (Gosselin et al. 1988) containing quartz, plagioclase, biotite, and microcline, with accessory muscovite, sphene, allanite, epidote, zircon, and opaques (McCombs et al. 2004). U-Pb ages on zircons in the BFG are 2563 ± 6 Ma (McCombs et al. 2004). The protoliths for the BFG are still debated, but possible origins include tuffaceous volcanics and/or arkosic sandstones (Gosselin et al. 1988). Regardless of the protoliths, the geochemistry reflects a calc-alkaline affinity similar to that of the Little Elk Granite.

2.3 Mafic Units

The metamorphosed mafic intrusions and flows that occur in the Precambrian core are localized in four general areas (Figure 2.2). These include the Blue Draw Metagabbro near the town of Nemo, the fault-bounded amphibolites that stretch from Pactola Reservoir to just north of Mount Rushmore, the amphibolites near the town of Rochford, and the amphibolites within the Vanderlehr Formation near Bear Mountain.

The 1 km thick Blue Draw Metagabbro (BDM) is by far the largest of the outcrops, and is the only mafic unit that has been directly dated. Redden et al. (1990) acquired a discordant 2170 ± 120 Ma U-Pb age on a bulk zircon. More recently, Dahl et al. (2003) used an ion microprobe to obtain a much more precise age of 2480 ± 6 Ma. The BDM has a layered structure composed of serpentinite at the base, hornblendite, hornblende-plagioclase gabbro to diorite, biotite granodiorite, and dioritic pegmatite at the top (Woo 1952; Dahl et al. 2006). Tectonic interpretations for the BDM and smaller mafic sills near the Nemo area were until now based upon the interpretations of the adjacent metasedimentary sequences. The nearby arkoses, quartzites, and shales have been interpreted as rift-related based upon the presence of marine fanglomerates and other passive margin marine facies. The BDM has been interpreted to be a mafic sill that intruded as an Early Proterozoic basin was forming (Redden et al. 1990). Given the Archean age of the BDM, this interpretation is untenable. Dahl et al. (2006) compared the BDM to layered mafic intrusions of the same age that lie within rift successions in the Superior craton. In this model, Dahl et al. (2006) suggest that the BDM was part of a proposed rifting event that separated the Superior and Wyoming provinces prior to 2480 Ma from the an Archean supercontinent Kenorland prior to 2480 Ma. Evidence for this model includes the temporal agreement with the layered mafic intrusions in the Superior Craton.

It may be worth considering the sharp contrast between this rifting scenario at 2480 Ma and the tectonic environment that is thought to have produced the nearby 2559 ± 6 Ma LEG (McCombs et al. 2004). The LEG, which is ~80 Ma older than the BDM, has been interpreted to be a volcanic-arc granite, or possibly a syncollisional granite (Gosselin et al. 1998). In addition, Chamberlain et al. (2003) described arc magmatism in the Black Hills as late as 2.50 Ga, only 20 Ma older than the BDM. These arc-related interpretations imply a drastic change in the tectonic environment from convergence to divergence in the Nemo area, yet there are no proposed driving mechanisms for such a dramatic change.

The amphibolites in the three other localities in the Black Hills are much smaller than the BDM. No direct ages have been determined for these amphibolites, and the relative ages remain speculative, as many of the dates are derived from stratigraphic correlations across the Precambrian core. Cross-cutting relationships indicate that the majority were emplaced around 1.88 Ga

(Redden et al. 1990). Because of metamorphism, lithologic descriptions of these units are limited, and they are generally distinguished by their appearances and by surrounding stratigraphic similarities. The only existing tectonic interpretation for these amphibolites is that they are related to rifting associated with volcanism during formation of a Proterozoic basin in which the metapelitic rocks are thought to have been deposited (Redden et al. 1990).

To the south of the BDM there are several thin sills of metamorphosed basalts that extend from the Pactola Reservoir area to just north of Mount Rushmore. These outcrops are structurally bounded by the north-northwest trending faults in this area (see Figure 2.1). The Pactola Lake fault, which joins the Silver City fault to the south, serves as the southwestern boundary the outcrop in the Pactola Dam quadrangle as well as for the larger of two outcrops in the Mount Rushmore quadrangle. The smaller outcrop in the Mount Rushmore quadrangle is situated between the Silver City Fault to the northeast and the Keystone fault to the southwest. These outcrops are generally fine-grained amphibolite grade metabasalts. Due to the linear extend of the outcrops, metamorphic grade ranges from biotite-grade in the Pactola Reservoir area to garnet-grade and staurolite-grade in the Keystone and Hill City areas of the Mount Rushmore quadrangle. The outcrops in these areas are fairly weathered and, with the exception of road cuts near Pactola Dam, the outcrops are not well exposed. Previous formational interpretations for the Pactola and Rushmore areas attribute these units to pillow lava flows in a deep marine environment (Redden et al. 1990), though no tectonic environment has been suggested.

Near the town of Rochford there are several thin outcrops of metabasalts. These are surrounded by biotite to garnet-grade metapelites. These outcrops consist of the Rapid Creek Greenstone, as well as metagabbros (McGehee and Bayley 1969). These outcrops are thin compared to the other mafic suites, typically 30-60m wide. A wider sill is exposed along Forest Service Route 17. Redden et al. (1990) suggest volcanism in this area around 1884 ± 29 Ma, but no specific tectonic setting is inferred.

South of the Rochford area, surrounding the Bear Mountain granitic terrane, is the fourth major suite of metabasalts. These are associated with the Vanderlehr Formation, which consists of locally derived basal conglomerates, arkoses and quartzites, as well as carbonate-silicate banded iron formations (Redden et al. 1990). The tectonic environment attributed to the Vanderlehr Formation is a marginal marine environment (Ratté 1986); however, there is no interpretation that specifically addresses the formation of the basalts.

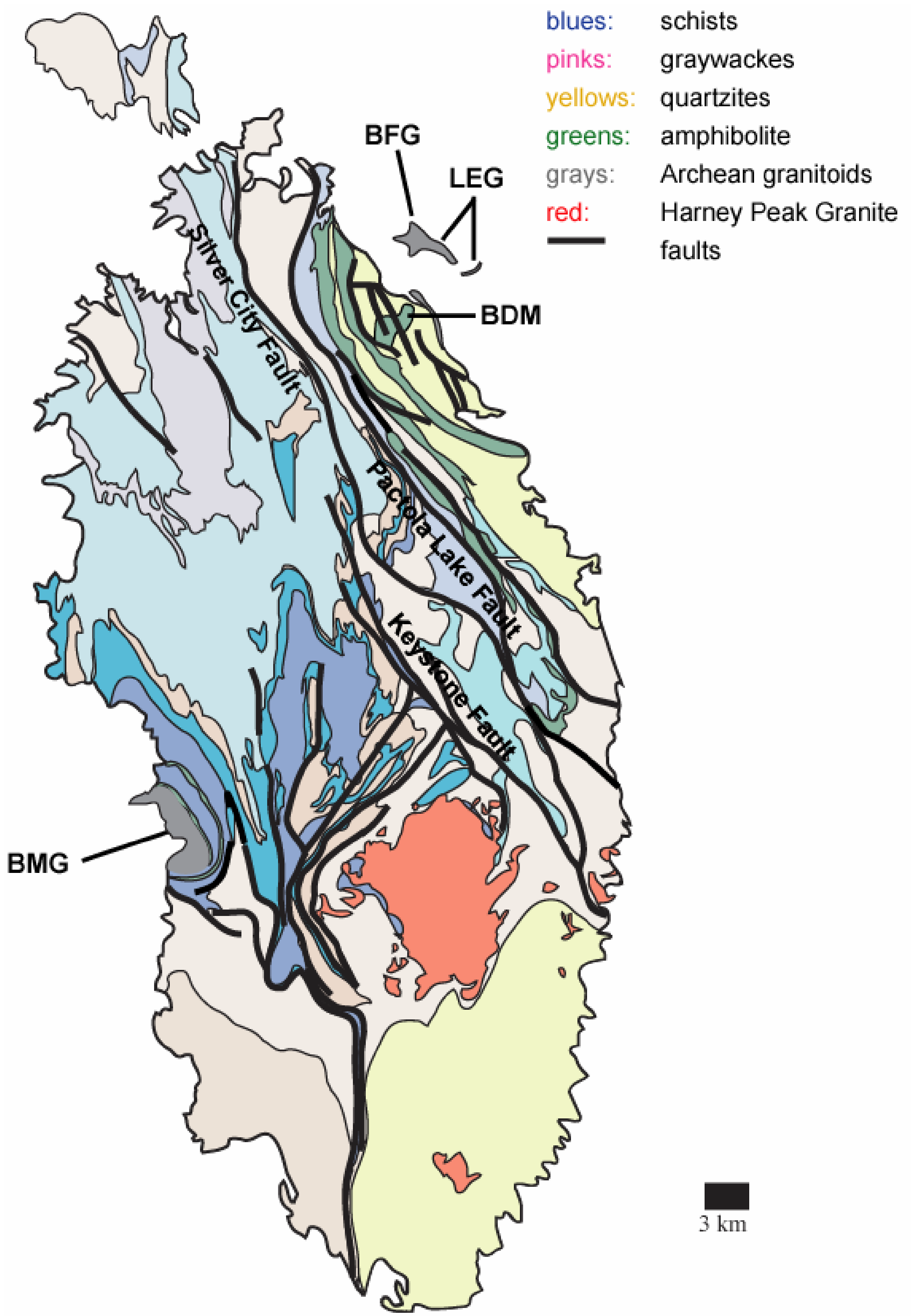

Figure 2.1 Geologic map of the Precambrian core of the Black Hills uplift. Modified from Redden et al. (1990)

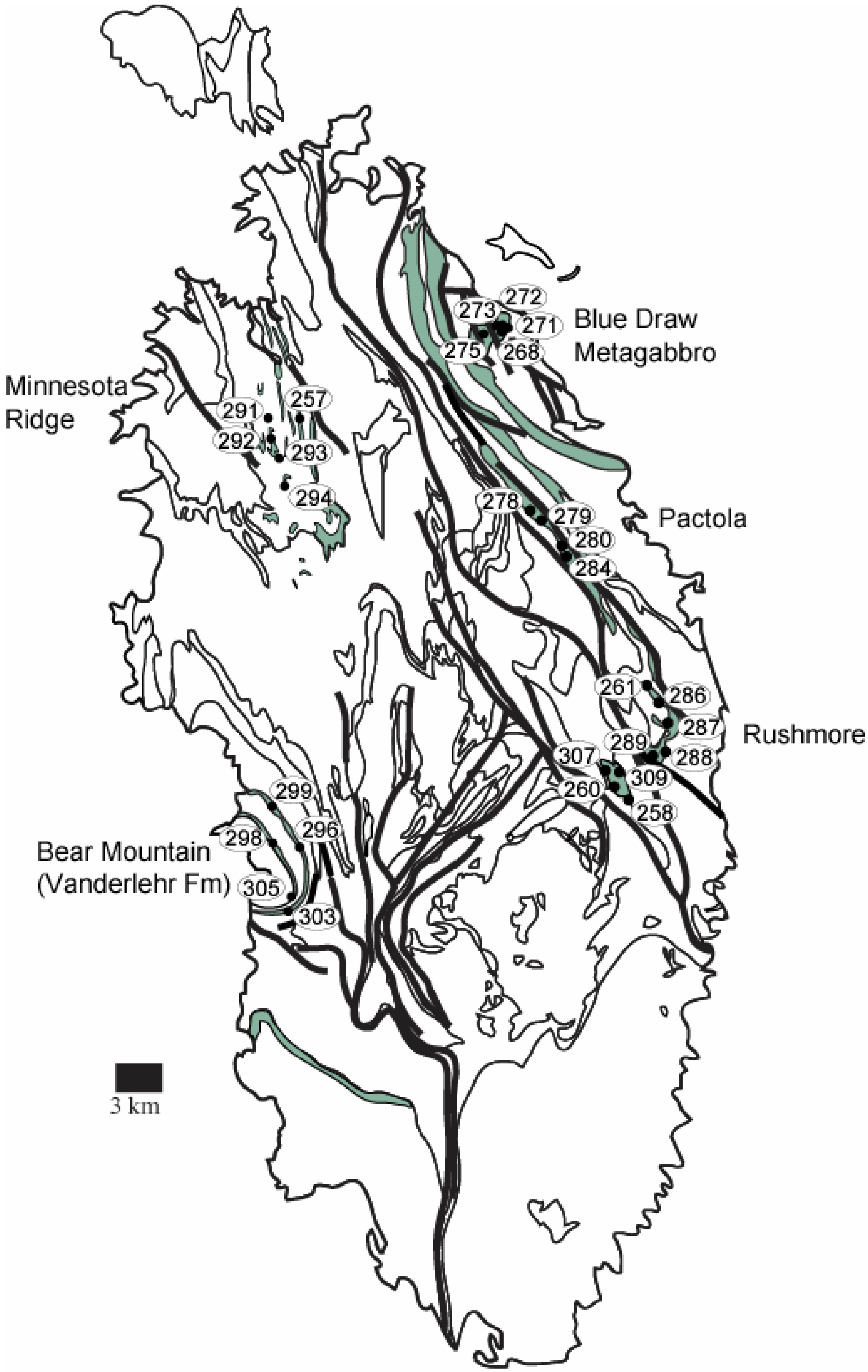

Figure 2.2 Location map for the amphibolites in the Black Hills (green units) and sample locations. Modified from Redden et al. (1990).

3 Analytical Techniques

3.1 Sample Selection

Approximately 85 samples, representing different varieties of rocks that were observed, were collected. Of these, 39 samples were chosen for geochemical analysis. No less than six samples were chosen from each of the four areas in order to represent the diversity of the outcrops. Samples were also chosen based upon the degree to which they were weathered. Several of the samples exhibited oxidation throughout the entire sample, while other samples did not accurately represent the bulk of the outcrop. However, the majority of the samples were suitable for analysis once the weathered sides were trimmed away. Texturally, the samples varied from coarse crystalline gabbroic and dioritic samples to fine-grained metabasalts. The majority of outcrops exhibited uniform textures, however, some like the Blue Draw Metagabbro, displayed a range of textures even in a single outcrop. Multiple samples representing the diversity of these outcrops were analyzed. After trimming, each sample was powdered using a SPEX shatterbox.

3.2 ICP-OES Analysis

The collected samples were prepared for ICP-OES analysis by lithium metaborate ($LiBO_2$) flux fusion. All samples were analyzed in duplicate. The samples collected in 2004 (samples 257-268) were prepared by combining 200 mg of the powdered sample with 600 mg of the flux powder. The powder mixture was heated in a graphite crucible at 1100ºC for 30 minutes in order to completely melt the sample. The molten sample was removed from the furnace and quenched in a 50 mL solution of 20% HNO_3. Once the sample was completely dissolved in the HNO_3 solution, it was diluted with an additional 50 mL of distilled water to 100 mL of solution. The procedure for the samples collected in 2005 (samples 270-311) was slightly modified to make the solutions more concentrated to enhance the detection of some trace elements. The molten samples were first quenched in a 25 mL solution of 20% HNO_3 and then diluted with additional distilled water to 50 mL of solution.

In addition to the rock samples, a series of USGS standards (BCR-1, AGV-1, G-2, and GSP-1) and blanks were prepared in the same manner as the rock samples. The USGS standards were used to determine the calibration curve for each analyzed element.

3.3 Loss on Ignition Analysis

Several of the minerals in the mafic rocks have been altered during the metamorphism that occurred in the Black Hills. In particular, olivine and pyroxene reacted to form amphibole and chlorite. To account for the incorporated H_2O, a “loss on ignition” (LOI) analysis was performed on 200 mg of each powdered sample by heating it in an alumina crucible at 1000ºC for 30 minutes and then reweighed to determine what percent of the sample is lost during heating.

3.4 Instrumental Neutron Activation Analysis

The collected samples were analyzed for elements La, Lu, Nd, Sm, Yb, Ce, Co, Cr, Eu, Fe, Hf, Sb, Sc, Ta, Tb, Th, Zn, Al, Ca, Dy, Mn, Na, Ti, and V by instrumental neutron activation analysis at the University of Missouri Research Reactor using techniques outlined by Graham et al. (1982).

4 Results

4.1 Petrography

Petrographic analysis of the amphibolites in the Black Hills was primarily done to establish the mineralogy of the rocks and to assess the degree to which they were altered. The samples vary between locations in their mineralogy, crystal size, and degree of metamorphic alteration and deformation. These variations may indicate differences in their chemistry, environments in which they crystallized, and the potential degree of chemical alteration.

Analysis of the amphibolites reveals that the BDM samples have considerably larger crystal sizes than the other three suites. The grain sizes range from less than 1 mm to 3 mm in diameter for the major minerals. Structurally, the BDM (Figure 4.1) appears relatively undeformed, though the original mineralogy has been altered. Actinolite and plagioclase ($An_{30}Ab_{70}$ to $An_{32}Ab_{68}$, as determined by Woo, 1952) are the dominant minerals present, and several of the amphibole crystals are zoned. The alteration appears to be metamorphic, and not due to weathering. The BDM also displays cumulate horizons, as it transitions from serpentinite and hornblendite at the bottom to a hornblende-plagioclase gabbro in the middle, and diorite to biotite granodiorite at the top.

The samples from the Pactola-Rushmore areas are considerably finer-grained (Figure 4.2). The actinolite crystals are generally <1 mm long, and between 0.1 and 0.3 mm wide. Plagioclase is generally <0.5 mm in diameter.

These samples exhibit very little fabric, indicating that these rocks have had fairly gentle deformational history. Metamorphic alteration is, however pervasive through the rocks.

The samples from the Minnesota Ridge area are fine-grained, with crystals <1 mm long and from 0.1 to 0.3 mm wide (Figure 4.3). The dominant mafic mineral in these samples is also actinolite. There is, however, a significantly larger amount of oxides, which appear to be ilmenite.

The samples from the Vanderlehr Formation near Bear Mountain contain hornblende and plagioclase (Figure 4.4). There are also oxides present and their equant shapes suggest that they are magnetite. The crystal size is considerably larger than at Pactola-Rushmore and Minnesota Ridge, but smaller than in the BDM. The hornblendes are generally 0.1 to 0.5 mm in width, and may be >1 mm in length, and the plagioclase crystals are as large as 2 mm in diameter.

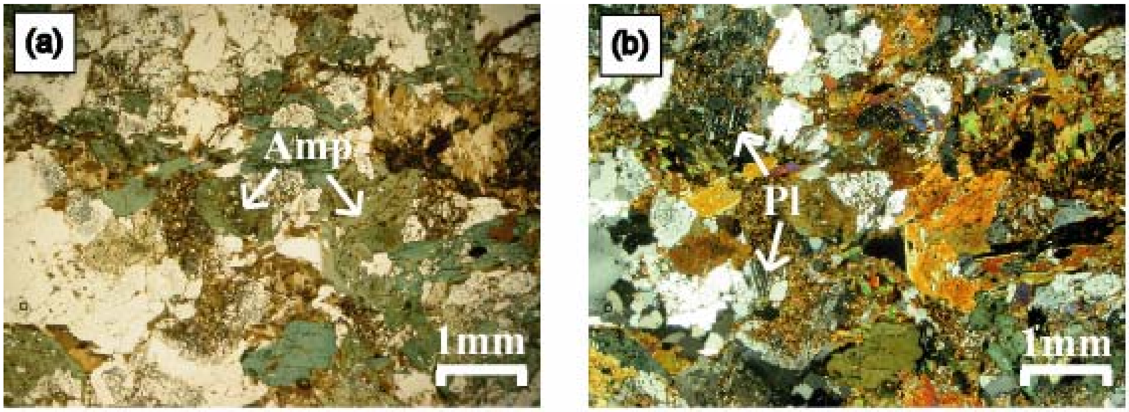

Figure 4.1 Amphibolite from the Blue Draw Metagabbro. Sample 268-3 under 2x magnification imaged in both plane-polarized light (a) and in cross-polarized light (b). Amphiboles (Amp) and plagioclase (Pl) are the dominant minerals. The sample is relatively undeformed, though it is altered.

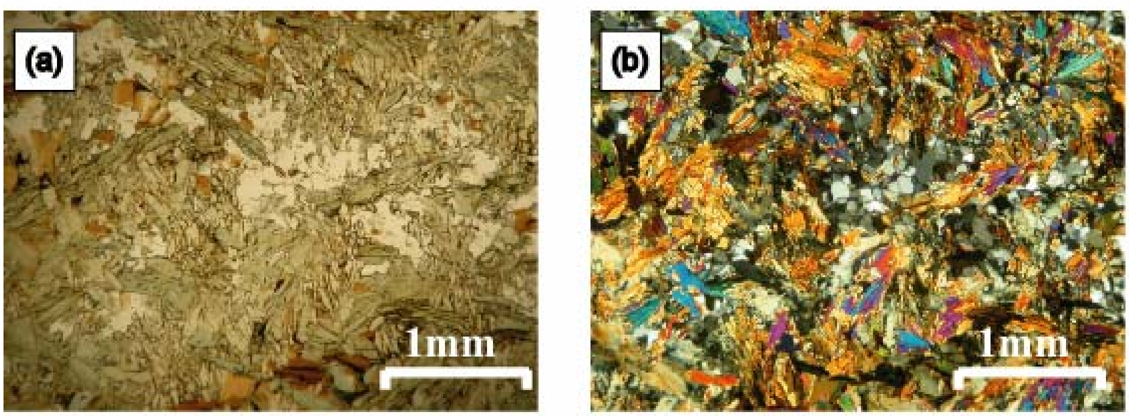

Figure 4.2 Amphibolite from the Mount Rushmore quadrangle. Sample 260-1 under 5x magnification imaged in both plane-polarized light (a) and in cross-polarized light (b). Amphibole is dominant, however plagioclase is present. The sample is highly altered, however there is little evidence of fabric with the rock.

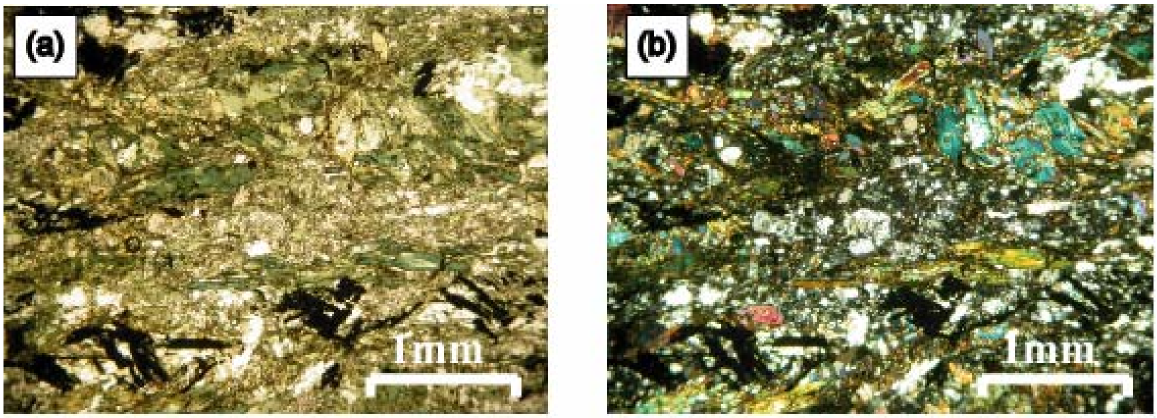

Figure 4.3 Amphibolites from the Minnesota Ridge area. Sample 257-2 at 5x magnification under (a) plane-polarized light and (b) cross-polarized light. Ampibole is dominant, as well as a high concentration of oxides. The oxides may be ilmenite, considering the high amount of titanium present in the Minnesota Ridge samples.

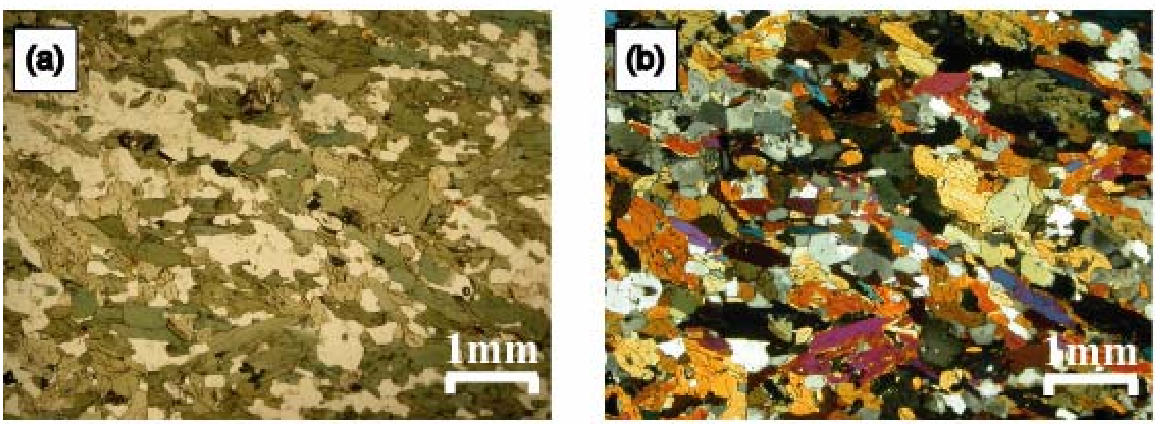

Figure 4.4 Amphibolites from the Vanderlehr Formation. Sample 72-5 at 2x magnification under (a) plane-polarized light and (b) cross-polarized light. Amphibole is dominant, while plagioclase and oxides are absent.

4.2 Major Element Geochemistry

The major element compositions of the amphibolites reveal systematic differences between the four suites. The concentrations of major oxides values in the BDM, Pactola-Rushmore, Minnesota Ridge, and the Bear Mountain areas are shown in Tables 4.1-4.4. The various oxide concentrations for the four suites are plotted with respect to SiO_2 in Figure 4.5 (a through h). The SiO_2 content in the BDM ranges from 50.4 to 59.9 wt. %, with an average of 54.8 wt. %. These values are significantly higher than the SiO_2 content in the other three suites (Figure 4.5). The SiO_2 concentrations range from 41.8 to 55.2 wt. % (49.0 wt. % average) for Pactola-Rushmore, 41.0 to 54.8 wt. % (46.1 wt. % average) at Minnesota Ridge, and 48.8 to 53.8 wt. % (51.6 wt. % average) at Bear Mountain. The concentration of K_2O is also highest in the BDM samples (Figure 4.5g). The concentrations range from 0.09 to 1.85 wt. %, averaging 1.04 wt. %. The K_2O in samples 272 and 273 is significantly lower in the other samples (0.14 and 0.09 wt. %, respectively). Excluding these two samples, which are outliers from the BDM in their trace element chemistries as well (see below), the average K_2O concentration is 1.31 wt. %. The relatively high concentrations of SiO_2 and K_2O in the BDM suggest that it has a calc-alkaline character.

The other three suites have much higher FeO and MgO, indicating an olivine-normative composition. They also have higher TiO_2 and moderately higher in MnO than the BDM. In particular, the Minnesota Ridge samples have TiO_2 that ranges from 0.88 to 3.60 wt. % (Figure 4.5f). It should be noted that the low-TiO_2 sample 294 is anomalous. Its chemistry, including trace elements (see below) suggests that it may be a cumulate. Excluding sample 294, the average TiO_2 concentration at Minnesota Ridge is 2.83 wt. %. The TiO_2 concentrations in these samples are over twice as much as in the other suites. The TiO_2 in the samples from the BDM, Pactola-Rushmore, and Bear Mountain average 0.63, 1.51, and 0.92 wt. %, respectively. The high TiO_2 concentrations in the Minnesota Ridge samples are consistent with their large abundance of ilmenite. The FeO (Figure 4.5c) and MgO (Figure 4.5b) concentrations are also highest at Minnesota Ridge. Excluding sample 294, the FeO concentrations range from 14.9 to 17.8 wt. %, averaging 16.5 wt. %, and the MgO concentrations range from 7.2 to 13.8 wt. %, averaging 9.4 wt. %. The samples from Minnesota Ridge are the lowest in CaO of all the suites (Figure 4.5d). The CaO concentration ranges from 0.6 to 8.5 wt. %, averaging 5.0 wt. %. The CaO concentrations for the BDM, Pactola-Rushmore, and Bear Mountain average 8.8, 8.2, and 10.4 wt. %, respectively.

The samples from Pactola-Rushmore and from Bear Mountain have very similar chemical compositions. The FeO contents range from 9.0 to 19.3 wt. % (13.2 wt. % average) at Pactola-Rushmore and from 11.4 to 13.5 wt. % (12.3 wt. % average) at Bear Mountain. The MgO contents range from 5.0 to 10.8 wt. % (7.2 wt. % average) at Pactola-Rushmore and from 5.8 to 8.0 wt. % (7.0 wt. % average) at Bear Mountain. The MnO concentrations range from 0.11 to 0.25 wt. % (0.17 wt. % average) at Pactola-Rushmore and from 0.14 to 0.17 wt. % (0.15 wt. % average) at Bear Mountain. The only oxide that is higher at Pactola-Rushmore than at the other areas is Na_2O (Figure 4.5e). In this instance, the samples at Bear Mountain do not exhibit similar compositions. The Na_2O concentrations for Pactola-Rushmore range from 1.65 to 4.64 wt. %, averaging 3.06 wt. %. The concentrations for the BDM, Minnesota Ridge, and Bear Mountain average 2.49, 2.13, and 2.17 wt. %, respectively.

Table 4.1 **Major Element Oxides of the BDM (wt. %)**

Sample	268-2	268-3	268-4	268-5	271-1	271-4	272	273	275-1
SiO_2	59.0	59.9	54.2	54.8	53.3	52.8	56.4	52.0	50.4
TiO_2	1.04	1.21	0.51	0.69	0.68	0.55	0.34	0.29	0.38
Al_2O_3	13.6	13.4	14.7	11.7	15.2	16.0	5.6	4.3	15.0
FeO	11.3	11.4	9.2	11.2	10.6	9.8	9.9	9.4	8.6
MnO	0.15	0.15	0.15	0.18	0.12	0.13	0.15	0.16	0.11
MgO	3.7	3.3	6.8	8.4	6.1	6.1	13.7	14.7	8.3
CaO	5.7	4.0	9.9	9.1	8.8	9.5	9.5	13.2	10.0
Na_2O	3.28	3.72	2.44	1.74	3.03	2.76	1.09	0.83	3.52
K_2O	1.57	1.85	0.97	1.30	1.18	1.15	0.14	0.09	1.14
P_2O_5	0.14	0.18	0.08	0.12	0.07	0.05	0.03	0.01	0.02
H_2O	0.49	0.89	1.08	0.77	0.86	1.21	3.09	5.00	2.58

Table 4.2 Major Element Oxides of the Pactola and Rushmore Quadrangles (wt. %)

Sample	278-2	279-3	280	284-3	261-1	261-2	286-3	287-1	288-3	289	258-1	260-2	260-3	307	309-1
SiO_2	43.7	48.6	48.5	48.2	41.8	50.3	46.1	47.8	55.2	52.3	45.3	50.6	52.0	53.8	50.3
TiO_2	1.22	1.80	1.38	1.83	2.55	1.46	0.94	0.83	1.90	1.74	2.83	0.65	1.04	0.93	1.62
Al_2O_3	13.6	13.6	16.9	14.7	15.0	13.1	14.0	13.0	10.9	12.6	15.9	16.4	13.7	13.1	13.3
FeO	12.7	12.8	9.9	13.5	19.3	13.5	11.4	12.8	12.8	15.8	15.3	9.0	12.3	12.7	14.9
MnO	0.13	0.14	0.11	0.13	0.22	0.17	0.14	0.16	0.22	0.20	0.24	0.14	0.18	0.18	0.19
MgO	7.0	6.9	5.0	5.0	5.8	7.1	8.9	10.6	6.5	5.4	5.4	9.2	10.8	8.2	6.6
CaO	7.9	8.6	5.6	4.9	9.3	8.5	8.9	11.2	8.7	7.2	9.9	9.7	6.8	6.7	9.7
Na_2O	2.87	3.30	4.64	3.25	2.49	3.61	3.08	1.65	2.75	3.69	2.56	2.78	2.66	3.89	2.65
K_2O	0.21	0.53	0.91	1.74	0.39	0.15	0.15	0.49	0.16	0.18	0.25	0.49	0.07	0.08	0.19
P_2O_5	0.07	0.15	0.16	0.22	0.20	0.12	0.08	0.06	0.17	0.15	0.67	0.07	0.09	0.05	0.13
H_2O	10.7	3.68	6.94	6.47	2.96	2.07	6.22	1.52	0.71	0.77	1.72	0.97	0.30	0.41	0.49

Table 4.3 Major Element Oxides of the Minnesota Ridge Amphibolites (Wt. %)

Sample	257-1	257-2	257-3	291	292-1	293-2	294
SiO_2	45.3	46.9	49.4	41.0	42.2	43.3	54.8
TiO_2	3.60	2.54	2.78	2.42	3.08	2.54	0.88
Al_2O_3	14.0	13.8	12.0	18.6	16.1	11.2	14.3
FeO	17.5	15.6	14.9	16.1	17.8	17.2	9.8
MnO	0.23	0.23	0.21	0.14	0.13	0.14	0.10
MgO	7.6	7.4	7.2	8.6	11.5	13.8	5.5
CaO	6.3	6.6	7.9	2.8	0.6	2.1	8.5
Na_2O	2.36	2.36	2.45	4.03	0.58	0.97	2.19
K_2O	0.14	0.14	0.13	0.07	0.73	2.28	0.11
P_2O_5	0.37	0.33	0.23	0.22	0.36	0.27	0.06
H_2O	2.57	4.05	2.73	6.00	6.93	6.23	3.65

Table 4.4 Major Element Oxides of the Bear Mountain Amphibolites (wt. %)

Sample	296-1	298	299-1	303	305-2
SiO_2	52.1	53.8	48.8	50.3	53.0
TiO_2	1.19	0.98	0.80	0.87	0.78
Al_2O_3	14.3	13.5	15.4	15.0	13.7
FeO	13.5	12.5	11.4	12.6	11.4
MnO	0.16	0.17	0.15	0.14	0.15
MgO	6.6	5.8	8.0	7.4	7.1
CaO	8.9	9.3	12.5	9.8	11.3
Na_2O	2.13	3.23	1.63	2.59	1.29
K_2O	0.11	0.13	0.39	0.22	0.29
P_2O_5	0.06	0.12	0.05	0.04	0.03
H_2O	0.99	0.42	0.84	1.02	0.86

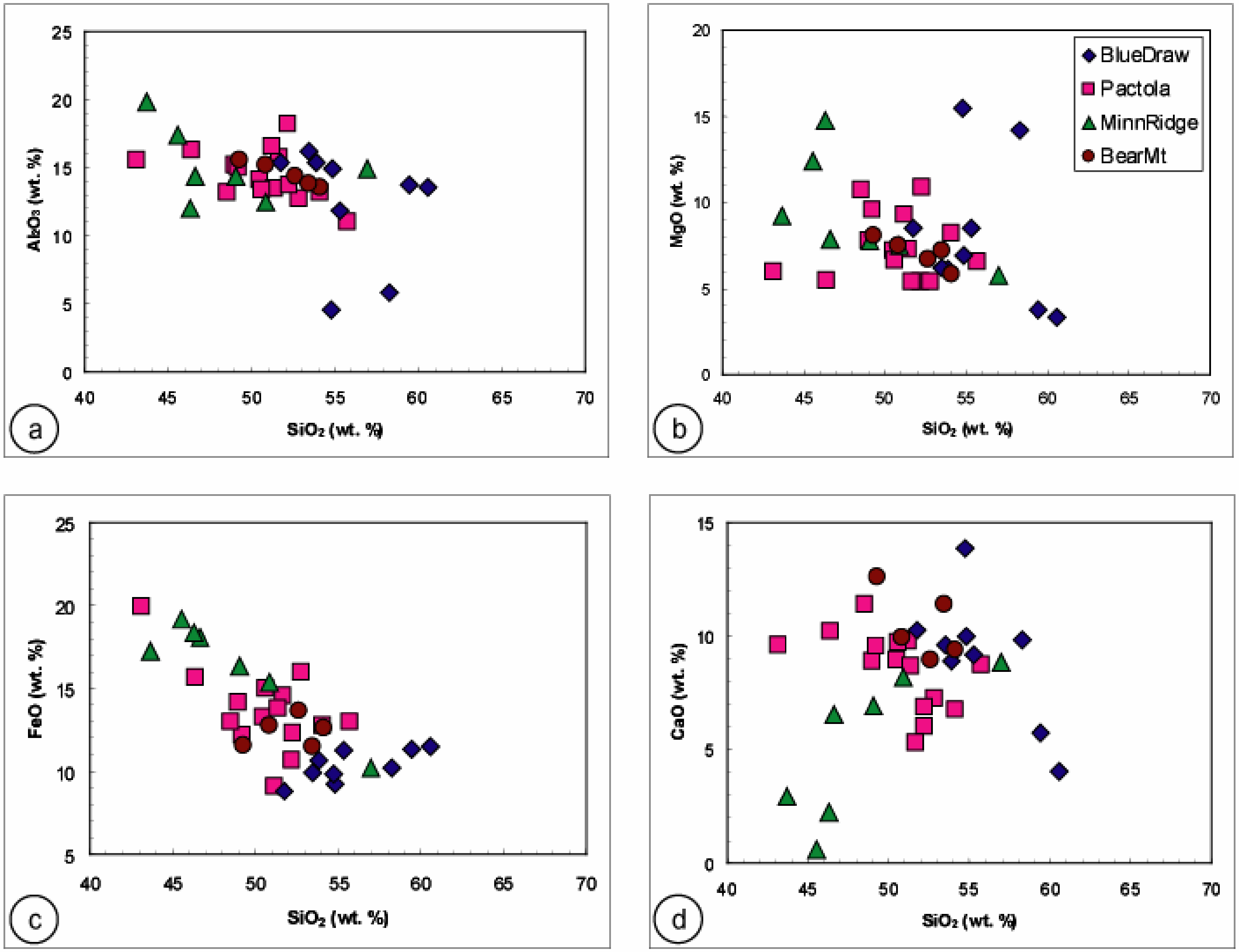

Figure 4.5 Major element oxide plots of samples from the four areas of amphibolites.

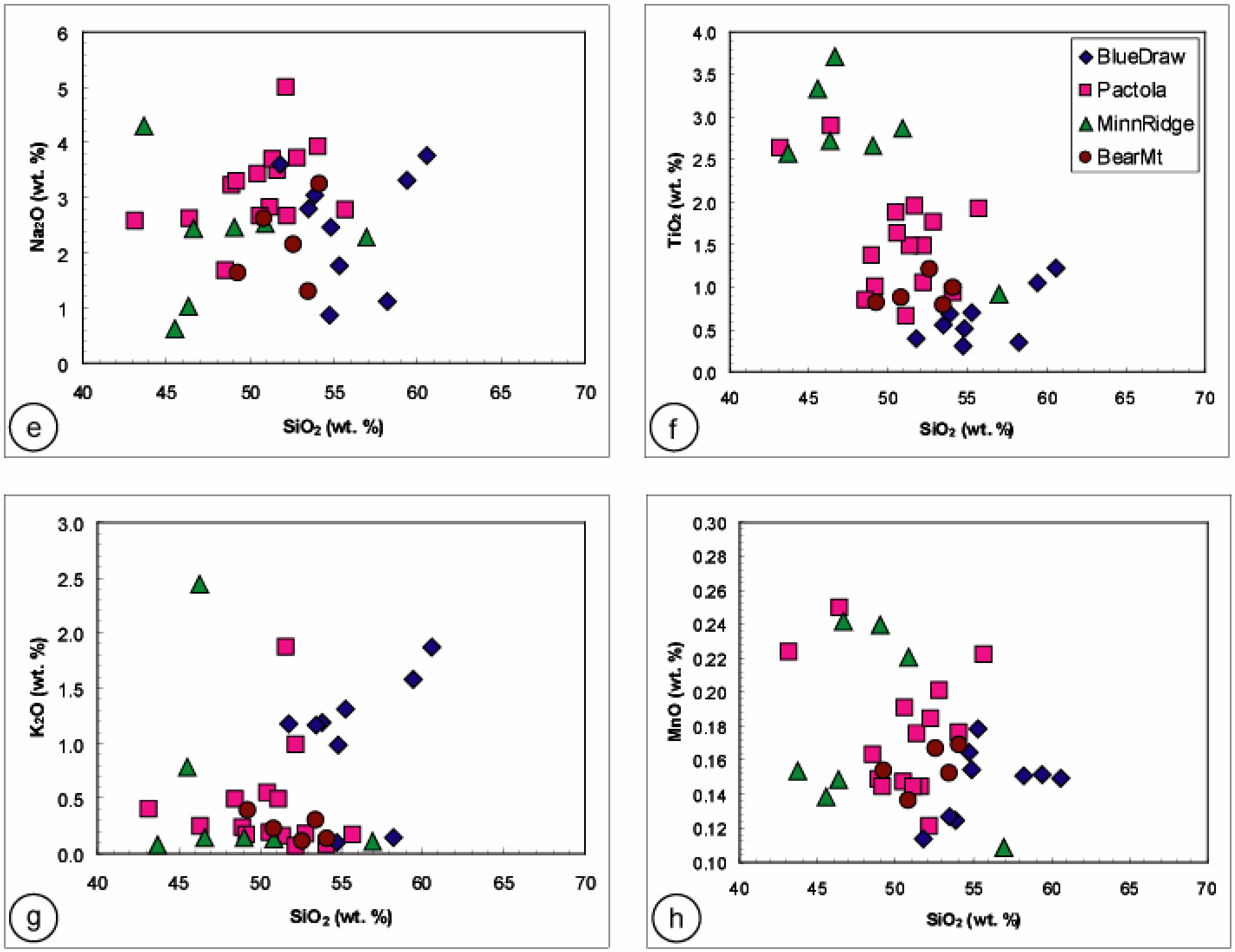

Figure 4.5 continued.

In addition to major oxide concentrations, CIPW norms are useful in estimating the original mineralogy of the rocks, which was subsequently changed during metamorphism. The CIPW norms for the four major suites are shown in Tables 4.5-4.8. They show that, in general, the BDM is quartz-normative, while the Pactola-Rushmore, Minnesota Ridge, and Bear Mountain samples are more olivine-normative.

All of the samples from the BDM (Table 4.5) are high in normative albite (Ab) and anorthite (An), averaging 20.3 wt. % for Ab and 18.8 wt. % for An. The ratio of An to the sum of the plagioclase components is about 48%, which falls into the andesine range (An_{30}-An_{50}), and is in agreement with Woo's (1952) petrographic estimates. In addition to the high plagioclase concentrations, the pyroxene content is also high. All samples contain diopside, averaging 19.9 wt. %, and all but sample 275-1 have hypersthene present, averaging 27.0 wt. %. Sample 275-1 is anomalous in that it has 18.1 wt. % olivine, but not normative hypersthene, which together with its high feldspar components suggests that it may be a troctolite cumulate. Samples 274-1 and 274-4 have olivine present, but less than 3.0 wt. %. The majority of the BDM samples have high normative quartz, plagioclase, pyroxene, and relatively high orthoclase concentrations, which is consistent with a calc-alkaline affinity.

The majority of samples from Pactola-Rushmore are olivine-normative, average of 15.2 wt. %, with the exception of sample 288-3, which is quartz-normative (Table 4.6). The olivine-normative samples are also high in plagioclase, averaging 25.2 wt. % for albite and 23.2 wt. % for anorthite components, diopside (13.8 wt. %), and hypersthene (17.5 wt. %). The lack of quartz and prominence of olivine in the Pactola-Rushmore samples suggests that it is tholeiitic. Sample 280 has a very high Al_2O_3 concentration of 16.9 wt. % which leads to its large proportion of normative plagioclase components. The high normative An and Ab components suggest accumulation of plagioclase.

The CIPW norms for Minnesota Ridge samples (Table 4.7) are also variable. Samples 257-3, 292-1, and 294 are quartz-normative, while 257-1, 257-2, 291, and 293-2 are olivine-normative (again recall that sample 294 is significantly different from the rest of Minnesota Ridge). The normative albite and anorthite range from 4.89 to 33.17 wt. % and 0.43 to 27.7 wt. %, respectively. Samples 291, 292-1, and 293-2 have normative corundum ranging from 4.0 to 14.2 wt. %. Though most of the normative minerals are quite varied, the samples have a consistently high abundance of normative ilmenite. Excluding sample 294, the ilmenite concentrations in the Minnesota Ridge samples range from 4.6 to 7.0 wt. % with an average of 5.4 wt. %. The normative ilmenite concentrations in the other suites average 1.2 wt. % for the BDM, 2.86 wt. % for Pactola-Rushmore, and 1.76 wt. % for Bear Mountain.

The samples from the Bear Mountain Vanderlehr Formation are slightly variable. Samples 296-1, 298, and 305-2 are quartz-normative, ranging from 1.47 to 5.91 wt. %, while 299-1 and 303 are olivine-normative, with concentrations of 10.2 and 9.26 wt. %, respectively. All samples have a fairly high concentration of plagioclase and pyroxene. The plagioclase abundances range from 10.9 to 27.4, averaging 18.4 wt. % for albite, and from 22.0 to 33.6, averaging 28.8 wt. % for anorthite. Pyroxene concentrations range from 16.4 to 23.3, averaging 18.5 wt. % for diopside, and from 14.4 to 33.6, averaging 24.3 wt. % for hypersthene. Sample 296-1 has a high concentration of ilmenite (2.26 wt. %), however the other samples average 1.76 wt. %.

Table 4.5 CIPW Norms of the BDM

Sample	268-2	268-3	268-4	268-5	271-1	271-4	272	273	275-1
Qtz	9.7	10.4	2.6	4.1	-	-	8.7	1.3	-
Or	9.0	10.8	5.8	7.4	7.0	6.8	0.8	0.5	6.7
Ab	27.1	31.1	20.7	14.2	25.6	23.3	9.2	7.0	24.5
An	17.4	14.3	26.4	19.5	24.5	27.9	10.1	7.8	21.8
Ne	-	-	-	-	-	-	-	-	2.87
Di	7.8	3.5	18.2	19.1	15.5	15.6	29.9	46.5	22.7
Hy	23.8	25.2	24.3	29.8	22.5	21.9	37.5	31.2	-
Ol	-	-	-	-	2.6	2.0	-	-	18.1
Il	1.92	2.27	0.97	1.26	1.29	1.04	0.65	0.55	0.72
Ap	0.32	0.42	0.18	0.28	0.17	0.11	0.07	0.13	0.04
Cr	-	-	-	-	-	-	-	-	-
C	-	-	-	-	-	-	-	-	-

Qtz quartz
Or orthoclase
Ab albite
An Anorthite
Ne nepheline
Di diopside
Hy hypersthene
Ol olivine
Il ilmenite
Ap apatite
Cr chromite
C corundum

Table 4.6 CIPW Norms of the Pactola and Rushmore Quadragles

Sample	278-2	279-3	280.00	284-3	261-1	261-2	286-3	287-1	288-3	289.00	258-1	260-2	260-3	307.00	309-1
Qtz	-	-	-	-	-	-	-	-	6.78	-	-	-	-	-	-
Or	1.23	3.14	5.39	10.30	2.23	0.90	0.90	2.88	0.95	1.07	1.45	2.91	0.42	0.45	1.13
Ab	24.3	27.9	38.3	27.5	13.4	30.1	25.4	14.0	23.3	31.2	21.7	23.7	22.4	32.9	22.4
An	23.5	20.6	22.6	20.2	27.7	19.0	24.0	26.6	16.9	17.3	31.1	31.0	24.9	18.0	23.7
Ne	-	-	0.50	-	3.78	-	0.35	-	-	-	-	-	-	-	-
Di	12.9	17.7	3.3	2.3	13.3	18.1	16.4	23.6	20.8	14.7	11.6	13.7	6.7	12.4	19.7
Hy	3.7	6.6	-	16.6	-	10.8	-	9.7	26.6	28.1	8.3	12.8	36.6	27.5	22.2
Ol	21.3	16.6	19.9	12.6	28.3	14.8	24.8	20.1	-	3.2	17.2	14.0	5.9	6.4	7.0
Il	2.31	3.43	2.62	3.47	4.68	2.73	1.79	1.58	3.61	3.31	5.36	1.25	1.96	1.77	3.07
Ap	0.16	0.35	0.38	0.52	0.45	0.28	0.17	0.13	0.40	0.34	1.54	0.16	0.20	0.12	0.30
Cr	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
C	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.7 CIPW Norms of the Minnesota Ridge Amphibolites

Sample	257-1	257-2	257-3	291	292-1	293-2	294
Qtz	-	-	0.50	-	6.11	-	10.56
Or	0.83	0.80	0.75	0.42	4.29	13.5	0.62
Ab	20.4	19.5	20.5	33.2	4.9	8.2	18.5
An	27.7	26.0	21.3	12.4	0.4	8.5	29.0
Ne	-	-	-	0.50	-	-	-
Di	1.7	3.5	13.5	-	-	-	10.6
Hy	27.4	32.6	33.9	-	56.4	32.5	25.2
Ol	13.7	6.0	-	35.1	-	21.6	-
Il	6.98	4.72	5.22	4.59	5.86	4.83	1.67
Ap	0.87	0.74	0.53	0.50	0.83	0.63	0.13
Cr	-	-	-	-	-	-	-
C	-	-	-	7.3	14.2	4.0	-

Table 4.8 **CIPW Norms for the Bear Mountain Amphibolites**

Sample	296-1	298	299-1	303	305-2
Qtz	3.10	1.47	-	-	5.91
Or	0.64	0.79	2.32	1.30	1.74
Ab	18.1	27.4	13.8	21.9	10.9
An	29.0	22.0	33.6	28.7	30.8
Ne	-	-	-	-	-
Di	12.2	19.7	23.3	16.4	20.8
Hy	33.6	26.2	14.4	19.6	27.4
Ol	-	-	10.2	9.3	-
Il	2.26	1.86	1.52	1.65	1.48
Ap	0.14	0.27	0.12	0.10	0.07
Cr	-	-	-	-	-
C	-	-	-	-	-

4.3 Trace Element Geochemistry

The trace element geochemistries of the amphibolites maintain the systematic differences between the four areas. Rare earth element (REE), transition metal, and other significant trace element concentrations are given in Tables 4.9-4.12. The samples from the BDM (Table 4.9) are enriched in barium (Ba) and Rubidium (Rb) (Figure 4.6a). Both elements may substitute for potassium in potassium feldspar and hornblende. Moreover, Rb substitutes more readily into feldspar than it does into hornblende. The high concentration of both elements in the BDM may then be in feldspars, which agrees with its calc-alkaline affinity. The BDM is distinctively lower in vanadium (V) than the other suites in the Black Hills (Figure 4.6b). The BDM samples are enriched in light rare earth elements (LREEs) relative to heavy rare earth elements (HREEs), as shown in Figure 4.7a in chondrite-normalized plots.

The samples from Pactola-Rushmore (Table 4.10) and Bear Mountain (Table 4.12) have very similar concentrations of trace elements. The samples from both areas have low concentrations of Rb and Ba (Figure 4.6a), and moderate concentrations of V and strontium (Sr) (Figure 4.6b). The samples from Bear Mountain are clustered much more closely than those at Pactola-Rushmore, and are slightly higher in Rb and slightly lower in Sr, which may substitute calcium in plagioclase. The REE patterns for Pactola-Rushmore (Figure 4.7b) and for Bear Mountain (Figure 4.7d) are slightly depleted in LREEs or flat.

The majority of samples from Minnesota Ridge are low in Rb and very low in Ba (Figure 4.6a). The exception is sample 293-2, which has an anomalously high concentration of Ba (595 ppm). All of the Minnesota Ridge samples have a high concentration of V (Figure 4.6b), which usually substitutes into Fe-Ti oxides; specifically ilmenite and titanomagnetite. Three of the samples show very high concentrations of Sr (Figure 4.6b), while four show lower concentrations. It should be noted that the three samples with the highest concentration were collected within a small field area, while other four were from more widely-spaced outcrops. The REE patterns for Minnesota Ridge are enriched in LREEs (Figure 4.7c), with the exception of sample 294, whose chemistry again shows more similarity to Pactola-Rushmore and Bear Mountain samples.

The relative concentrations of several other trace elements are described below in view of tectonic discrimination diagrams.

Table 4.9 Trace Element Concentrations for the BDM (ppm)

Sample	268-2	268-3	268-4	268-5	271-1	271-4	272	273	275-1
La	27.3	31.6	13.9	19.3	17.2	14.8	8.7	4.6	9.3
Ce	47.0	52.9	22.8	32.5	32.2	28.0	16.8	9.3	18.4
Nd	24.1	30.5	12.9	19.0	13.2	11.9	8.1	4.5	7.8
Sm	2.94	3.15	0.64	1.51	2.16	1.27	5.33	3.56	0.35
Eu	1.36	1.17	1.03	0.93	1.98	1.85	2.06	1.77	1.58
Tb	0.82	0.80	0.62	0.85	0.70	0.68	0.48	0.37	0.53
Yb	2.50	2.69	1.82	2.34	1.91	1.74	1.67	1.48	1.37
Lu	0.41	0.47	0.37	0.44	0.40	0.38	0.40	0.36	0.32
Ni	40	25	84	97	42	39	147	145	73
Co	39.9	35.8	44.3	53.0	41.1	43.0	57.4	47.8	40.5
Cr	48	34	101	195	221	91	1950	1888	270
Sc	26.0	24.0	28.8	35.5	29.5	28.3	40.4	52.3	29.1
Zn	112	89	72	107	83	167	47	109	29
V	218	208	173	215	179	162	199	220	151
Rb	56.8	66.6	40.9	54.2	34.9	35.5	6.5	4.6	28.2
Ba	553	476	282	374	319	269	37	15	209
Sr	199	116	215	144	190	217	51	54	205
Zr	128	165	73	94	94	78	51	28	48
Hf	2.69	3.71	2.54	3.90	1.54	1.03	1.89	1.70	0.68
Th	-	-	-	-	4.94	3.86	2.82	0.40	1.38
Nb	8.4	7.7	5.8	8.2	7.3	6.6	-	-	3.7
Ta	-	-	-	-	0.71	0.72	0.81	0.74	0.69
U	-	-	-	-	5.09	4.78	5.22	4.55	4.06
Y	25.5	29.6	14.8	20.3	22.1	19.0	15.4	11.1	13.6

Table 4.10 Trace Element Concentrations for Pactola-Rushmore Quadrangles (ppm)

Sample	278-2	279-3	280	284-3	261-1	261-2	286-3	287-1
La	4.1	11.6	10.0	15.9	7.7	4.1	6.2	5.9
Ce	11.6	26.1	21.5	35.2	25.6	12.3	13.3	14.0
Nd	8.3	14.4	12.0	18.4	21.0	10.3	8.2	7.1
Sm	1.72	3.99	3.60	6.18	2.41	2.77	1.18	1.35
Eu	2.32	2.75	2.29	3.10	2.30	1.29	2.02	2.23
Tb	0.43	0.65	0.63	0.80	0.93	0.86	0.48	0.48
Yb	2.50	2.95	2.47	2.98	4.85	2.87	2.17	2.22
Lu	0.53	0.52	0.39	0.53	0.77	0.51	0.43	0.49
Ni	47	26	28	17	60	80	25	42
Co	50.4	38.5	41.8	47.8	59.9	48.5	52.2	52.8
Cr	137	87	95	87	11	100	166	357
Sc	47.6	41.3	43.7	34.1	46.4	45.5	50.1	43.4
Zn	77	62	68	36	155	86	23	29
V	336	318	335	256	606	358	261	222
Rb	6.4	8.7	6.5	53.9	12.3	4.3	1.7	16.0
Ba	19	88	94	334	182	57	33	96
Sr	135	274	278	173	329	154	239	127
Zr	72	112	121	144	157	79	55	50
Hf	3.36	2.79	1.49	2.77	7.09	5.59	2.29	4.17
Th	-	0.31	0.21	1.65	-	-	-	0.09
Nb	9.0	13.0	10.0	13.9	21.0	12.8	7.9	7.6
Ta	0.74	0.72	0.75	0.74	-	-	0.65	0.70
U	6.81	6.18	5.10	6.80	-	-	5.37	6.62
Y	31.4	39.2	40.1	43.1	44.0	28.7	24.2	21.5

Table 4.10 cont.

Sample	288-3	289	258-1	260-2	260-3	307	309-1
La	7.7	5.0	72.8	4.0	3.0	3.4	7.3
Ce	20.4	10.5	124.4	6.4	9.6	9.8	20.1
Nd	14.2	10.7	86.5	3.3	7.9	7.4	13.1
Sm	4.15	3.10	5.81	0.80	3.05	1.84	3.78
Eu	2.96	3.11	3.07	0.80	1.15	2.40	2.87
Tb	0.66	0.49	1.28	0.49	0.78	0.48	0.66
Yb	2.81	4.01	4.46	1.79	2.55	2.38	3.05
Lu	0.60	0.69	0.66	0.34	0.44	0.55	0.61
Ni	32	35	217	103	70	52	50
Co	40.0	48.3	159.5	35.8	43.9	44.7	43.6
Cr	118	122	162	181	118	197	75
Sc	36.1	45.4	24.9	28.0	42.6	41.8	28.3
Zn	38	61	85	78	91	28	49
V	381	523	164	169	306	265	305
Rb	10.9	8.8	5.5	14.1	3.2	9.1	9.8
Ba	36	52	40	104	15	43	38
Sr	237	114	201	238	193	98	277
Zr	139	110	358	36	58	57	103
Hf	4.27	6.00	6.81	2.79	4.54	4.29	5.15
Th	-	-	-	-	-	-	-
Nb	15.2	17.1	17.9	6.1	9.6	9.5	14.2
Ta	0.71	0.78	-	-	-	0.75	0.71
U	7.94	8.90	-	-	-	7.14	8.07
Y	32.1	43.1	63.8	13.6	21.1	22.3	33.1

Table 4.11 Trace Element Concentrations for Minnesota Ridge (ppm)

Sample	257-1	257-2	257-3	291	292-1	293-2	294
La	26.5	22.9	24.0	15.4	10.3	21.4	3.8
Ce	55.3	46.7	46.2	35.7	57.5	51.2	9.6
Nd	37.1	31.2	34.4	18.9	15.1	26.8	6.6
Sm	2.79	3.85	2.25	6.68	9.44	12.26	0.84
Eu	2.28	2.04	1.98	3.14	3.35	3.84	2.04
Tb	1.05	0.96	0.85	0.82	1.05	1.08	0.51
Yb	2.91	2.49	2.62	2.34	2.76	2.39	2.73
Lu	0.57	0.59	0.53	0.63	0.71	0.68	0.44
Ni	91	94	57	60	173	386	40
Co	44.1	44.7	46.4	54.9	54.2	92.0	50.4
Cr	41	110	64	528	1284	4341	366
Sc	24.2	27.1	28.6	43.9	44.8	34.9	52.4
Zn	139	133	140	51	59	130	86
V	345	307	328	382	365	326	334
Rb	7.8	6.5	5.9	9.8	21.0	40.0	-
Ba	19	15	15	41	156	595	12
Sr	618	458	537	133	19	69	144
Zr	249	184	208	140	230	205	61
Hf	5.94	6.08	6.27	5.20	4.70	5.43	2.67
Th	0.00	-	-	0.07	2.11	1.62	-
Nb	-	15.4	15.6	16.0	28.3	22.6	8.2
Ta	-	-	-	0.55	0.77	0.71	0.78
U	-	-	-	8.27	9.04	8.96	5.64
Y	31.9	25.5	27.2	26.6	27.6	24.3	20.1

Table 4.12 Trace Element Concentrations for Bear Mountain (ppm)

Sample	296-1	298	299-1	303	305-2
La	5.3	6.3	4.3	2.4	4.4
Ce	13.2	13.9	12.1	6.5	10.8
Nd	9.1	10.2	6.2	5.3	6.6
Sm	1.66	1.28	0.27	0.84	0.55
Eu	2.59	2.60	2.14	2.32	2.21
Tb	0.54	0.55	0.53	0.44	0.51
Yb	2.91	2.90	2.49	2.56	2.20
Lu	0.55	0.55	0.47	0.52	0.48
Ni	45	29	57	51	52
Co	42.9	43.6	35.3	41.7	41.6
Cr	157	23	258	234	240
Sc	44.8	45.9	45.5	46.3	36.8
Zn	36	35	27	69	32
V	326	289	263	286	256
Rb	9.5	10.0	10.6	9.1	11.6
Ba	40	14	53	16	34
Sr	92	116	114	152	131
Zr	64	55	51	49	48
Hf	4.51	4.38	3.26	3.91	3.30
Th	-	-	-	-	-
Nb	10.6	10.6	7.5	9.1	7.8
Ta	0.69	0.65	0.71	0.69	0.71
U	7.28	7.23	5.96	6.77	6.23
Y	30.2	31.1	24.3	23.0	19.4

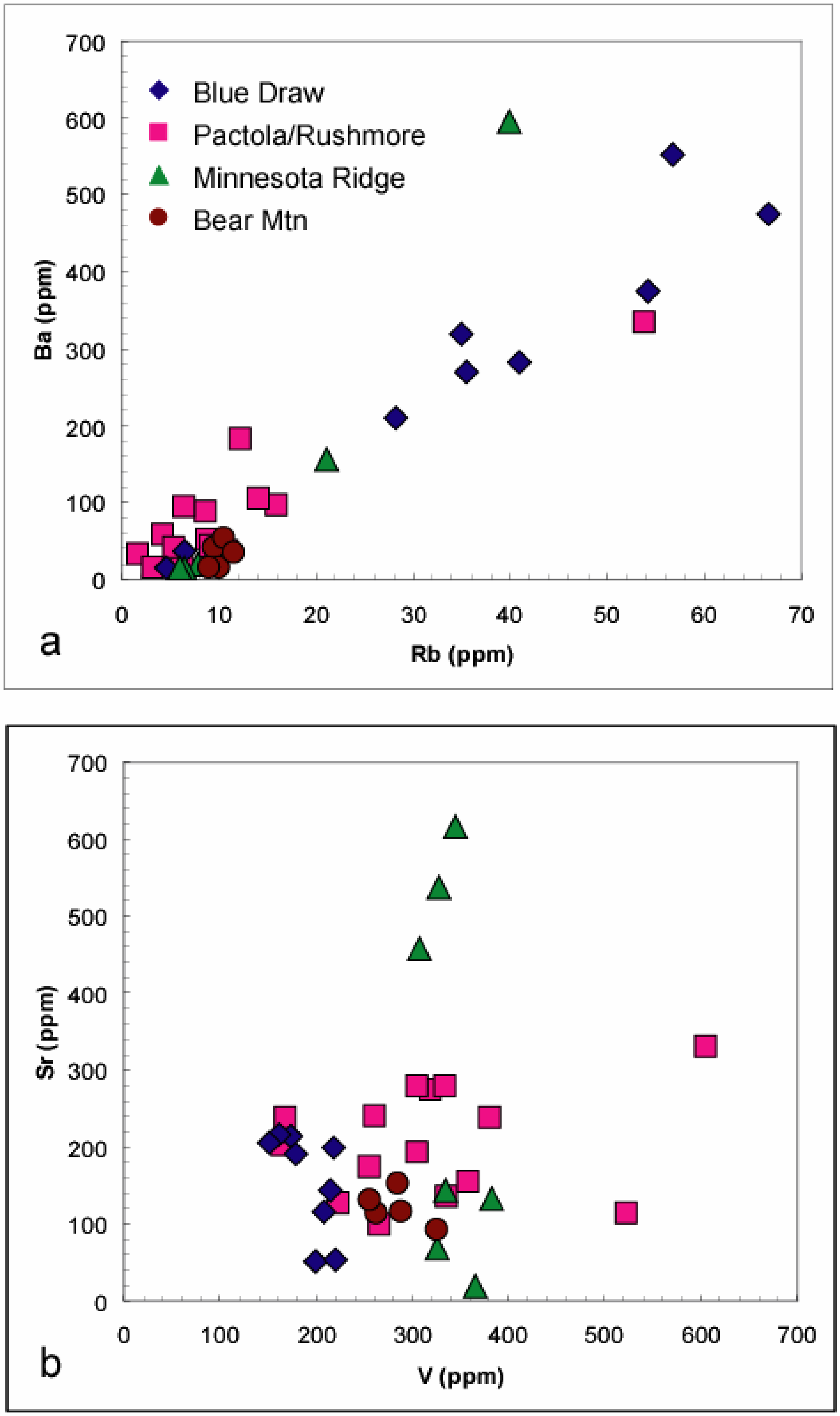

Figure 4.6 Trace element plots for the four mafic suites:
(a) Ba vs. Rb and (b) Sr vs. V

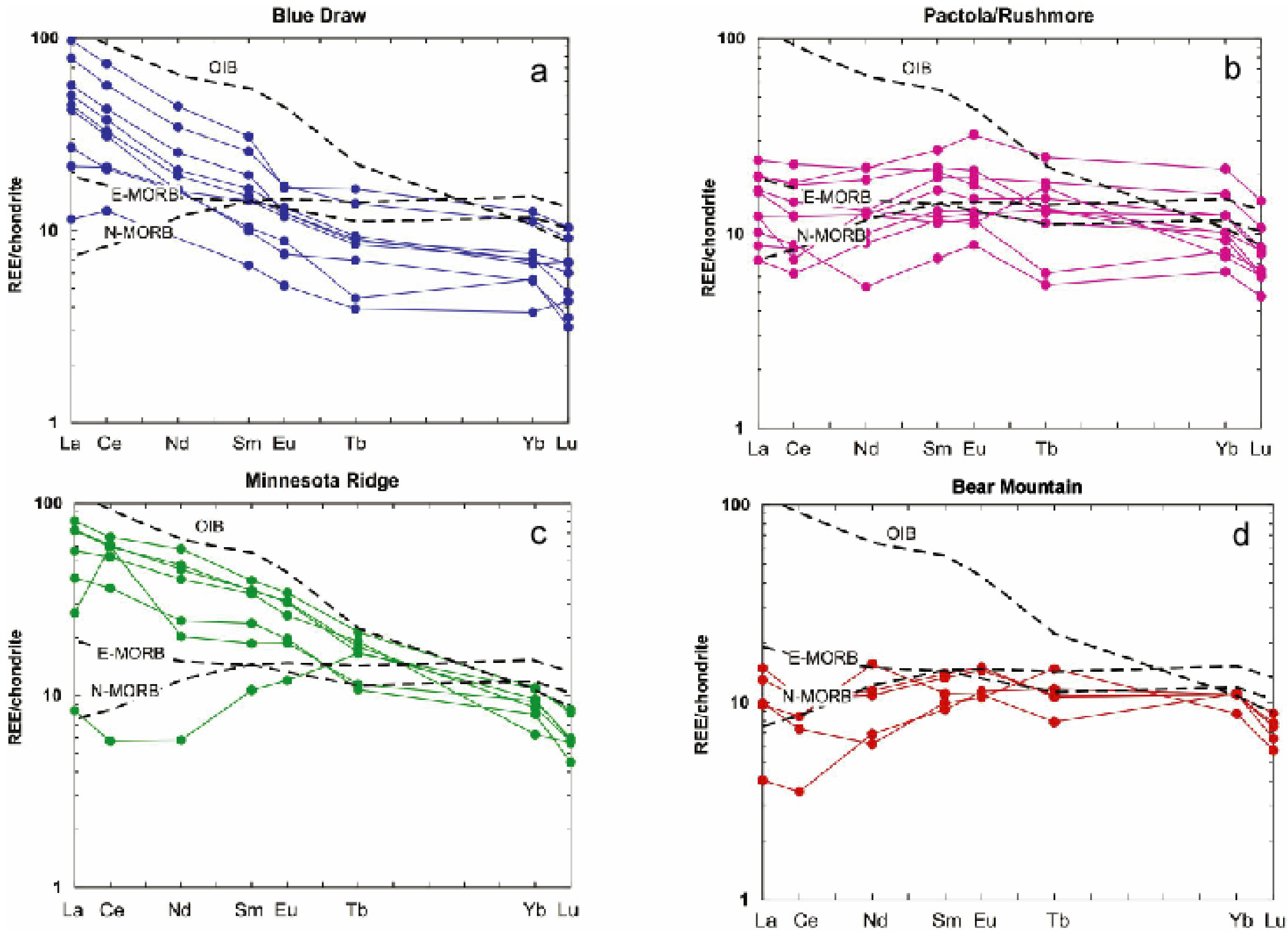

Figure 4.7 Chondrite-normailzed plots of the REE compositions of the samples from the four major suites of mafic rocs: a) BDM; b) Pactola-Rushmore; c) Minnesota Ridge; d) Bear Mountain. Values for N-MORB, E-MORB, and OIB from Sun and McDonough (1989).

4.4 Tectonic Discrimination

The position of major element data on the AFM diagram (Figure 4.8), in which A, (alkalis Na_2O+K_2O), F (total iron as FeO), and M (MgO), and which is used to discriminate between tholeiitic and calc-alkaline compositions, shows that the majority of the samples in the Black Hills are tholeiitic, with the exception of the BDM, which has calc-alkaline affinities. However, the BDM does not have a well-defined calc-alkaline trend, which is consistent with its cumulate horizons, including a very amphibole-rich horizon, and lack of evolved compositions. It should also be noted that the alkalis, especially Na_2O, are prone to mobilization during metamorphism, in which case the samples may not reflect the primary composition.

One of the more useful major oxide discrimination diagrams is the total alkalis vs. silica (TAS) diagram (Figure 4.9; Le Bas et al. 1986). The majority of the samples from the four suites plot within the basalt and basaltic andesite fields, with a few samples in the basanite, basaltic trachyandesite, and andesite fields. It is critical to note that the TAS diagram is intended for fresh volcanic rocks, though it may be used as a preliminary classification of chemically equivalent plutonic rocks. Although the TAS is also not intended for use with altered or metamorphosed rocks, the classification of the Black Hills samples in the TAS is in general agreement with Figures 4.8 and with the trace element classifications (see below).

Comparison of the MnO, TiO_2, and P_2O_5 concentrations in the four suites allows a much more differentiated classification of the mafic rocks. Mullen (1983) categorizes basalts and basaltic andesites into five tectonic suite: mid-ocean ridge basalts (MORB), ocean-island tholeiites (OIT), island-arc tholeiites (IAT), ocean-island (or seamount) alkali basalts (OIA), and calc-alkaline basalts (CAB). Discrimination of these fields is governed upon early crystallization of titanomagnetite, fractionation of olivine and clinopyroxene, and the source of the magma. These elements are sufficiently immobile during low-temperature alteration, and relatively immobile up through greenschist facies metamorphism (Mullen 1983). The fractionation of magnetite at high or constant oxygen fugacity (fO_2) is associated with a calc-alkaline trend, while fractionation of olivine at lower fO_2 is responsible for tholeiitic trends. MnO is partitioned into olivine, and increases in abundance as the fO_2 decreases, and is therefore preferentially removed from MORBs. MnO is therefore depleted relative to TiO_2 in MORBs. Conversely, arc magmas are enriched in MnO relative to TiO_2 due early crystallization of titanomagnetite. The P_2O_5 abundance is related to the degree of partial melting, as well as the initial composition of the magma, and does not indicate fractionation. OIBs are enriched in P_2O_5 compared to the other basalts. OIBs are also enriched in TiO_2 and depleted in MnO, which is consistent with a fundamentally different source. It should be noted that MnO is slightly mobile through the greenschist facies metamorphism.

The mafic suites in the Black Hills discriminate nicely into the fields described by Mullen (1983) in Figure 4.10. Most of the samples from the BDM plot in the CAB field, which is consistent with their calc-alkaline affinity. Some of the samples plot within the IAT field, which may be due to fractional crystallization. The samples from Pactola-Rushmore plot within the IAT and MORB fields. There is no distinction between Pactola and Rushmore samples that fall on either side of the major NNW-trending faults within the respective quadrangles. Mullen (1983) notes that primitive MORBs and arc magmas have similar $MnO-TiO_2-P_2O_5$ ratios due to similar parent magmas. The samples from Bear Mountain, which are similar to those at Pactola-Rushmore, also fall into the IAT field, but with no crossover into the MORB field. The samples from Minnesota Ridge show a definite affinity towards OIBs, with the exception of the anomalous 294 sample, which plots in the IAT field. The differentiation of the mafic samples into the different fields is a useful indication of their tectonic environments during petrogenesis, but as Mullen (1983) points out, the diagram should be used as a guide in conjunction with other data, and not as absolute proof.

The trace element data is very discriminatory as well. Pearce and Cann (1973) developed a tectonic discrimination diagram for basalts using Ti, Zr, and Y, all of which vary in relative concentrations between the tectonic environments, but are relatively immobile during metamorphism. Titanium is indicative of ilmenite and titanomagnetite fractionation though it may also substitute into rutile or sphene. Zr is a very incompatible element, and does not substitute into the major silicate minerals. Y is also fairly incompatible, and may be partitioned into garnet and amphibole. The fields delineated by Pearce and Cann (1973) are within-plate basalts (WPB), IAT, CAB and an indeterminate MORB-IAT field. The WPB are equivalent to the OIB and OIA fields of the $MnO-Ti_2O-P_2O_5$ diagram.

When plotted on the Ti-Zr-Y diagram, the four mafic suites differentiate well into the WPB, CAB, and MORB-IAT fields (Figure 4.11). The BDM plots within the CAB field, with the exception of one samples that is slightly enriched in Y and depleted in Zr. The BDM may be further discriminated into a continental-arc basalt, as opposed to an oceanic-arc basalt by Figure 4.12 (after Pearce 1986). With the exception of the Y-enriched sample, the BDM has a distinct continental-arc basalt affinity. The samples from Pactola-Rushmore fall into the MORB-IAT field. The Bear Mountain samples also plot within the MORB-IAT field, but are more clustered on the Y side of the field. The samples from Minnesota ridge plot in the WPB field, which is depleted in Y, and enriched in Ti. Again, the exception to this suite is sample 294, which again shows a MORB-IAT affinity.

The relative concentrations of V and Ti can be useful in discriminating between tectonic environments as well. Figure 4.13 is a V-Ti plot complied by Shervais (1982). The BDM samples fall generally within the CAB field due to their low concentrations of Ti. The Pactola-Rushmore samples have Ti/V ratios between 20 and 50, spanning the MORB and back-arc basin (BAB) field, excepting a few outliers. The Bear Mountain samples are lower in Ti, and lie along the MORB-BAB boundary. Most of the Ti-enriched Minnesota Ridge samples fall into the ocean-island and alkali basalt field.

The differentiation of the Black Hills samples is very consistent among these tectonic discrimination diagrams. These systematic geochemical differences between the four mafic suites have broader implications for the tectonic environments when these rocks were formed, though they are now in close proximity of each other in the Black Hills.

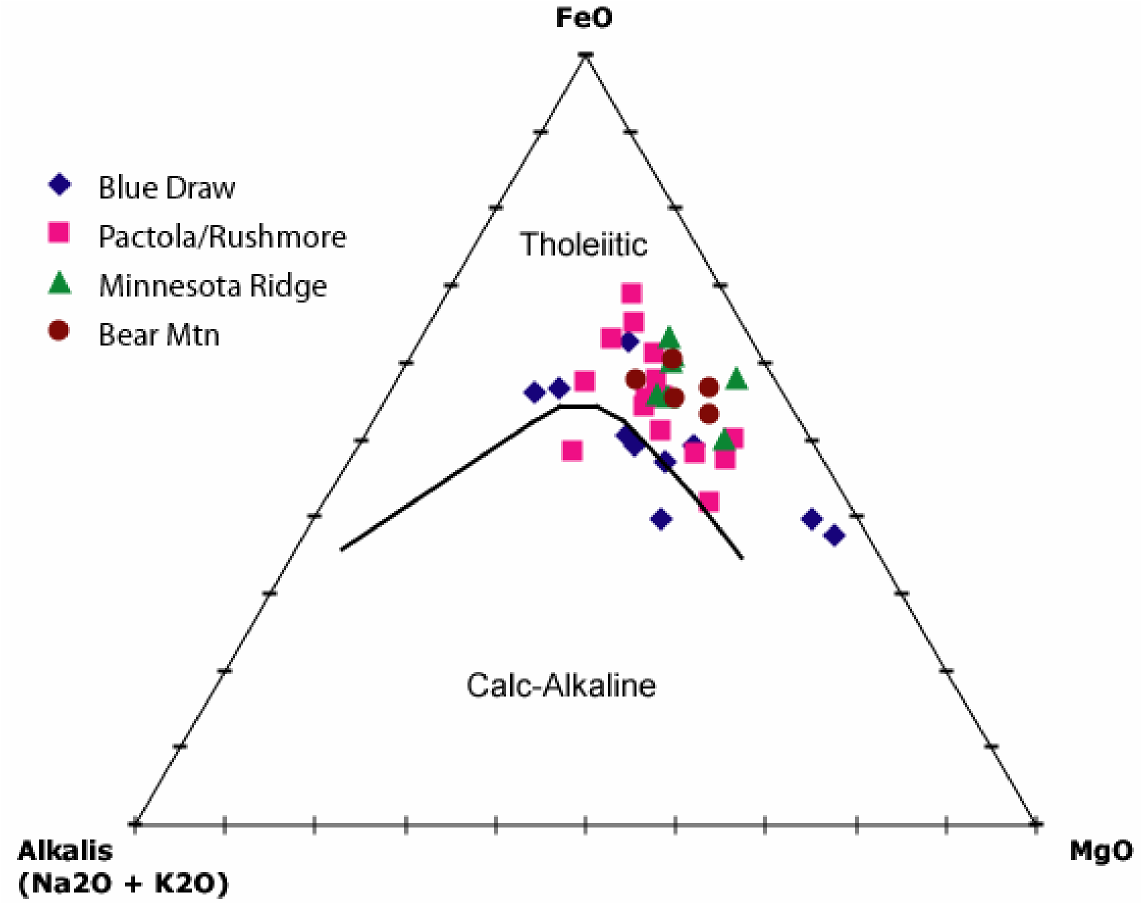

Figure 4.8 AFM diagram showing samples from the four major mafic suites. Modified after Irvine and Barager (1971)

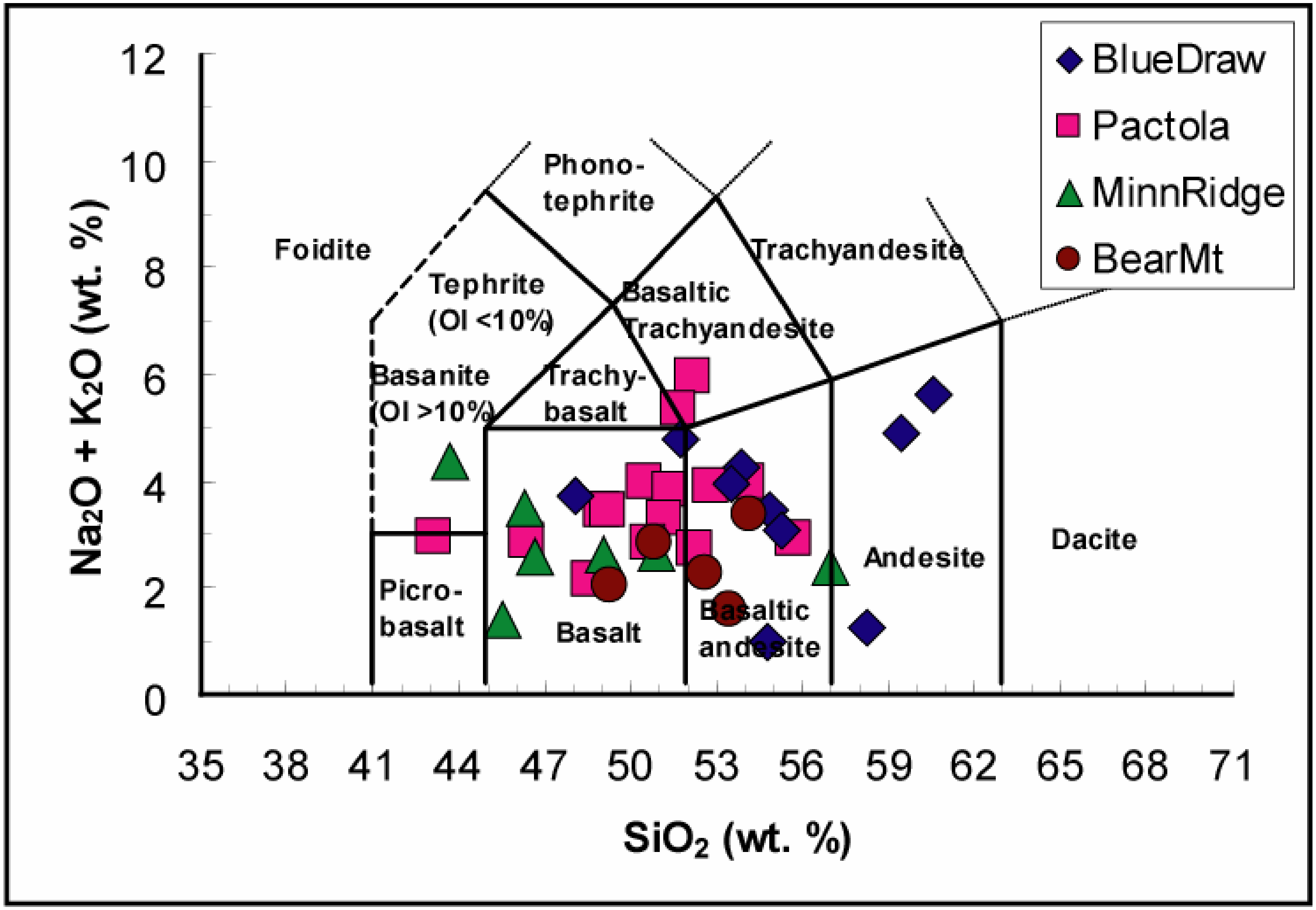

Figure 4.9 Chemical classification of the four amphibolite suites. The alkali vs. silica diagram is specific to volcanic rocks, however an intermediate to mafic composition is evident for the amphibolites. Modified after Le Bas et al. (1986).

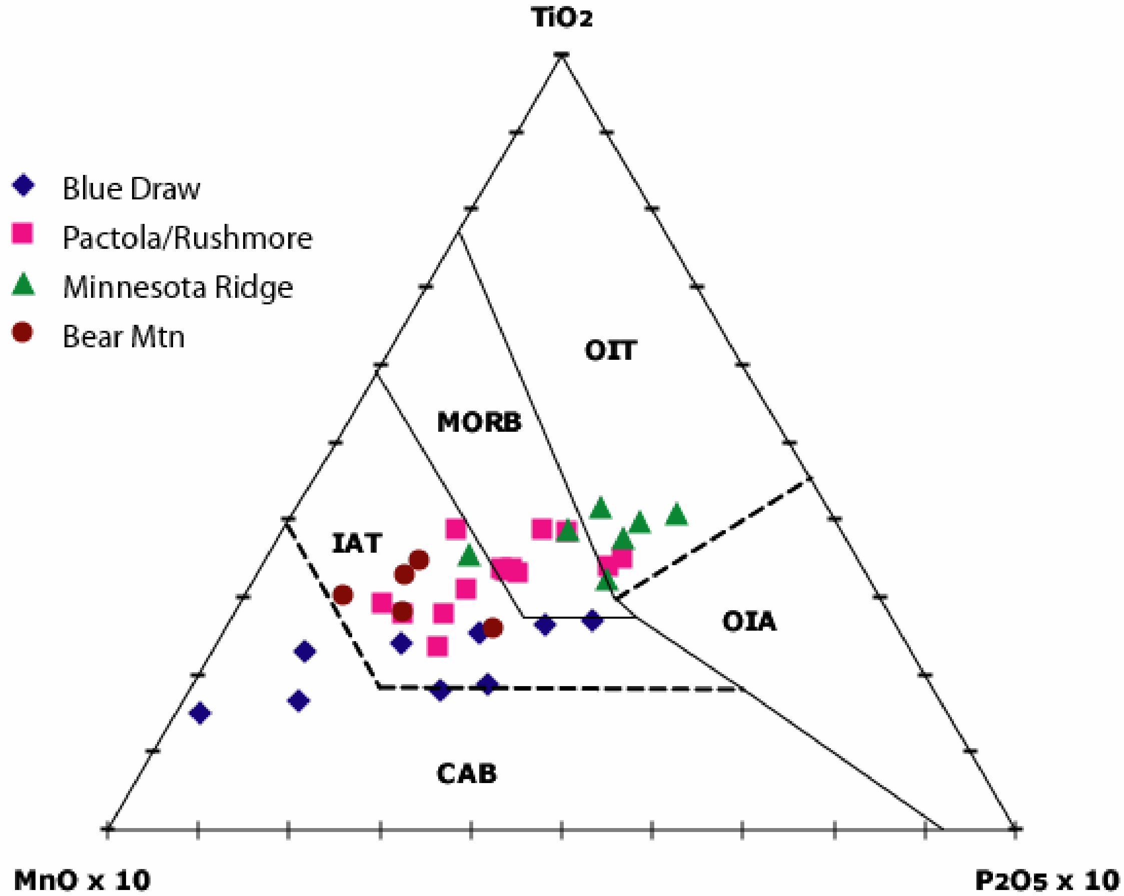

Figure 4.10 MnO-TiO_2-P_2O_5 discrimination diagram for the four mafic suites, modified after Mullen (1983). Fields are ocean-island tholeiite (OIT); mid-ocean ridge basalts (MORB); island-arc tholeiite (IAT); ocean-island (or seamount) alkali basalt (OIA); and calc-alkaline basalt (CAB).

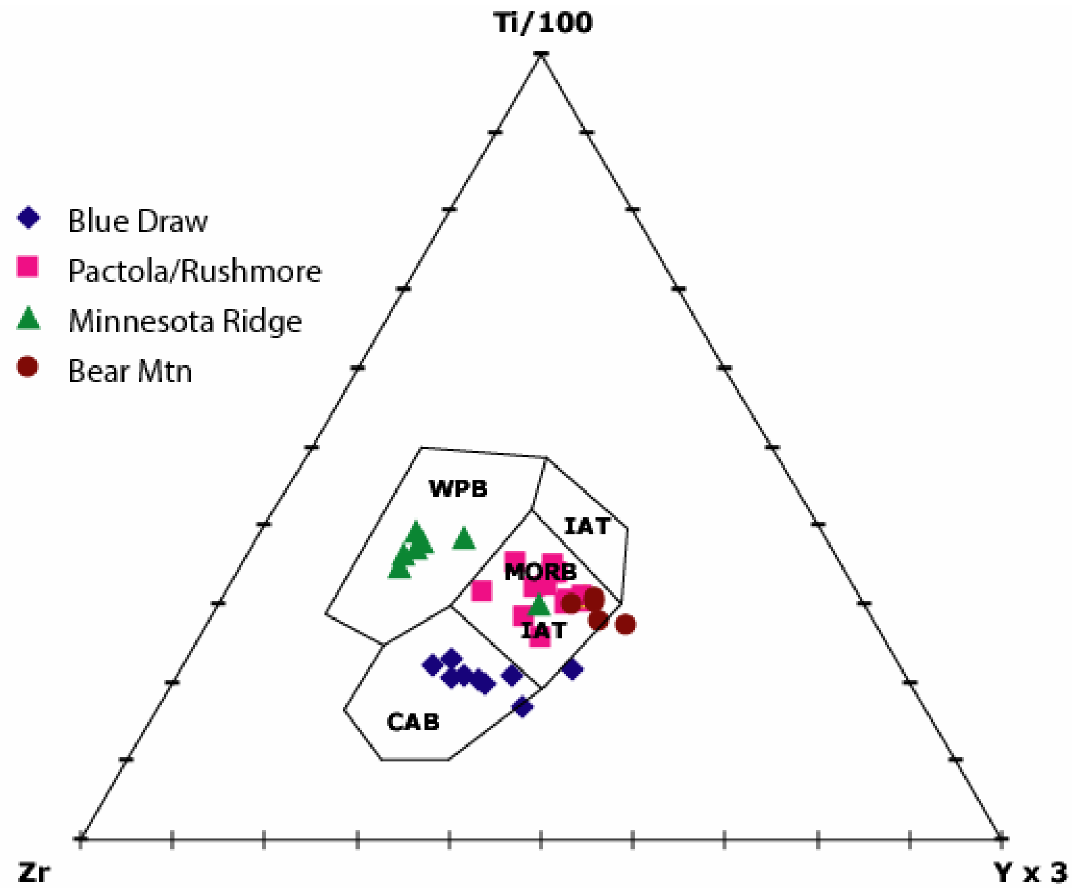

Figure 4.11 Ti-Zr-Y discrimination diagram for the four mafic suites modified after Pearce and Cann (1973). Fields are within-plate basalts (WPB), island-arc tholeiites (IAT), calc-alkaline basalts (CAB) and an ambiguous IAT and mid-ocean ridge field (MORB - IAT).

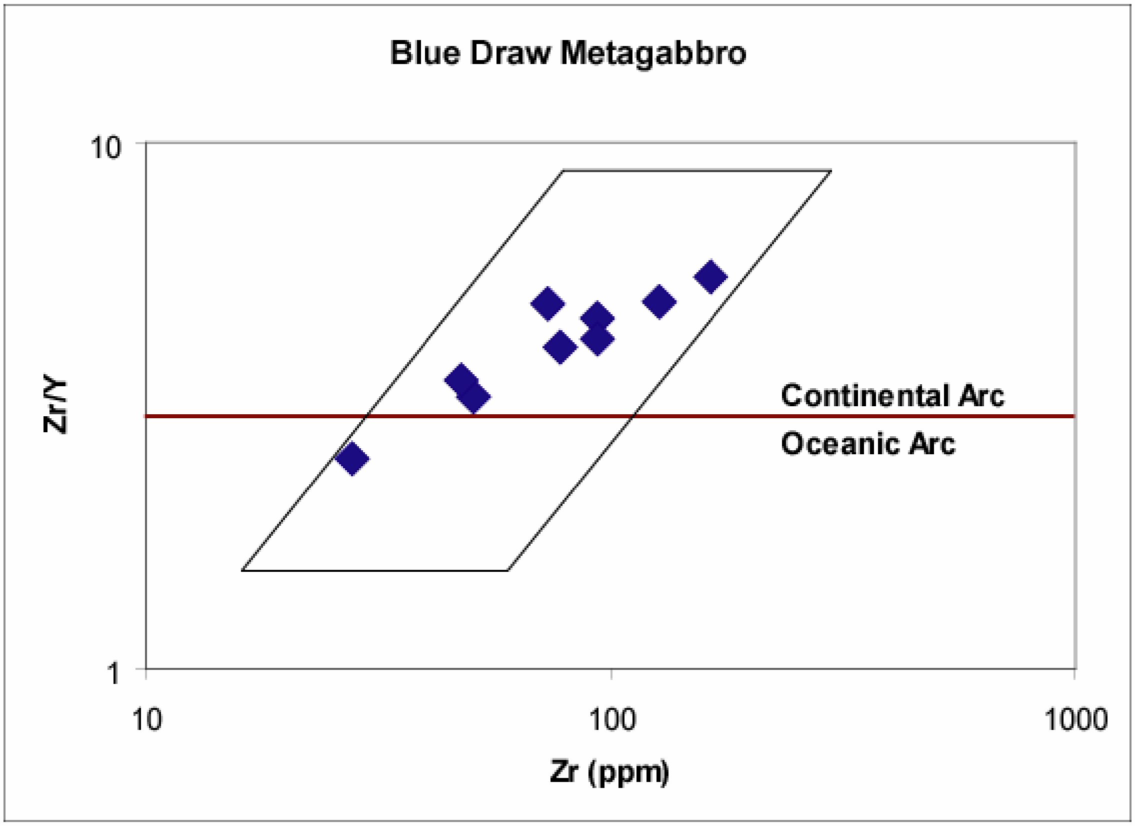

Figure 4.12 Discrimination diagram of the BDM samples, indicating a general continental-arc affinity. Modified after Pearce (1983).

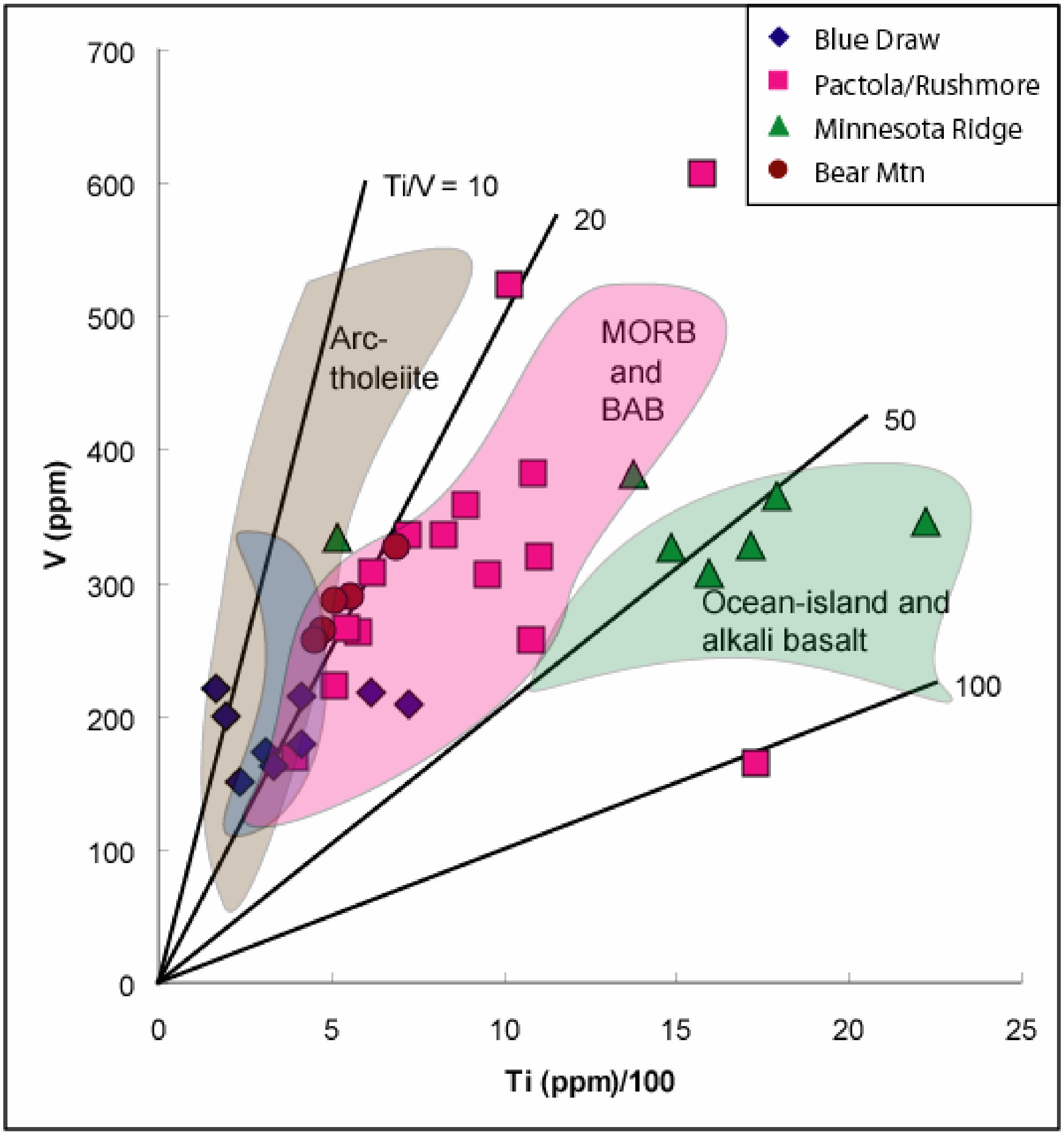

Figure 4.13 Ti-V discrimination diagram for the four mafic suites with fields of arc tholeiite in brown, MORB and back-arc basin basalts (BAB) in pink, ocean island and alkali basalts in green and CAB in blue. Modified from Shervais (1982).

5 Discussion

The course-grained texture of the BDM indicates that it was plutonic, and given the multiple compositional horizons within the intrusion it is also likely that it has undergone fractional crystallization and accumulations of minerals. Nevertheless, the major and trace element geochemical signatures of the BDM show a distinct calc-alkaline composition. All of the discrimination diagrams suggest that the BDM crystallized from a calc-alkaline magma at a continental-arc setting (Figure 4.12). This interpretation is contrary to previous assumptions that the BDM was generated during rifting of the Wyoming craton or a separation of the Wyoming craton from the Superior craton (Redden et al. 1990; Dahl et al. 2006). The interpretation agrees, however, with the tectonic setting indicated for the nearby and only slightly older LEG (Gosselin et al. 1988). Chamberlain et al. (2003) recognized arc magmatism within the Wyoming province (including the Black Hills) as late as 2.50 Ga, which is only 20 Ma older than the age of the BDM.

The LEG and BMG are now thought to be part of the Wyoming craton, but the continental mass at whose margin they and the BDM were generated is uncertain, as there is no isotopic data that related them directly to the Wyoming province. Chamberlain et al. (2003) associated the arc magmatism with the Wyoming province, but it could have been related to a smaller mass of juvenile crust known as the Dakota Block (Baird et al. 1996) that may extend to the region between the Wyoming and Superior cratons, and was later amalgamated to the

Wyoming craton during the BH orogeny. These scenarios are shown in Figures 5.1 and 5.2. Figure 5.1 illustrates formation of the BDM in relation to a west-dipping subduction zone beneath the Wyoming craton, while Figure 5.2 illustrates formation of the BDM in relation to a subduction zone beneath the Dakota Block. In this case, the Dakota Block and the BDM would have been accreted to the Wyoming province some time after the intrusion of the BDM.

The mafic rocks at Pactola-Rushmore have a tholeiitic affinity. Previous interpretations acknowledge submarine volcanic centers in the Pactola and Rushmore quadrangles, evidenced by pillow lavas, and associate them with subsidence of a Black Hills basin in conjunction with deposition of marine sediments that include black shales (Redden et al. 1990). These samples plot in the IAT and MORB fields on the tectonic discrimination diagrams and, in the context of the sedimentary environment, may be reflecting a back-arc basin setting behind an island arc to the east (Figure 5.3). These basalts may have been subsequently sheared and then accreted onto terrain to form the long NNW-trending fault-bounded bands that extend through the two quadrangles.

The mafic rocks at Bear Mountain also indicate an island-arc tholeiite or MORB affinity. However, it is difficult to correlate these units to those with similar characteristics at Pactola-Rushmore, as suggested by Redden et al. (1990), without a magmatic age of formation. Nevertheless, association of these sills with marine sediments also suggests a back-arc basin setting (Figure 5.3), consistent with their tholeiitic compositions.

The samples from Minnesota Ridge are unique from the other basalts in the Black Hills. The discrimination diagrams all show that these basalts were generated in a within-plate volcanic setting. The REE patterns for the Minnesota Ridge samples suggest an oceanic hot spot activity instead of a hot spot associated with a mid-ocean ridge, which typically have E-MORB REE patterns. However, the association of these basalts with iron formations and cherts indicates a submarine volcanic setting. In comparison with most hot spot related basalts, however, the Minnesota Ridge basalts are strongly depleted in Ba, Rb and Y, suggesting perhaps that they are the product of the melting of a depleted eclogitic mafic lower crust, possibly originating from previous underplated mafic magmas, or a depleted eclogitic lithospheric mantle. The Minnesota Ridge basalts may have been generated during initiation of the back-arc spreading center (Figure 5.4). Partial melting of such an eclogitic mafic lithosphere would be expected to also yield the LREE-enriched patterns and depletion in Y seen at Minnesota Ridge.

The geochemical characteristics and tectonic interpretations for the four major mafic suites within the Black Hills have significant implications for the tectonic setting of the Black Hills prior to the BHO. The BDM is substantially older than the other three suites, and is the only suite that is related to a continental margin tectonic environment. The Pactola-Rushmore and Minnesota Ridge suites have similar ages, but different trace element compositions. The tectonic environment for the formation of the samples from the Bear Mountain area is similar to that at Pactola-Rushmore, but there are no age constraints for the samples at Bear Mountain.

The broader implications for the proposed tectonic settings for the mafic suites reflect a more complicated tectonic history than the previously proposed ensialic rifting (Redden et al. 1990), particularly at. 2.48 Ga, when the BDM was apparently formed in a continental arc. Additionally, the formation of the basalts at Minnesota Ridge by remelting of an eclogitic lower crust or lithospheric mantle reveals a previously unappreciated complex pre-BHO tectonic evolution of the Black Hills. Figure 5.5 is the proposed tectonic model for the Black Hills at ~1.88 Ga, the age of the associated tuffs. It is suggested that by this time, the BDM and its host continental crustal rocks that may have already been accreted to the Wyoming craton, were rifted away by a retreating subduction zone, which generated a back-arc basin. The basalts from Minnesota Ridge, which may have formed by melting of the lithospheric mantle or mafic lower crust as the rift basin began to open, are shown just to the west of the spreading center of the back-arc basin. The basalts from Pactola-Rushmore and from Bear Mountain were subsequently extruded at the spreading center. All of these mafic suites and the host ocean-bottom sediments were subsequently amalgamated onto the Wyoming craton during the BHO.

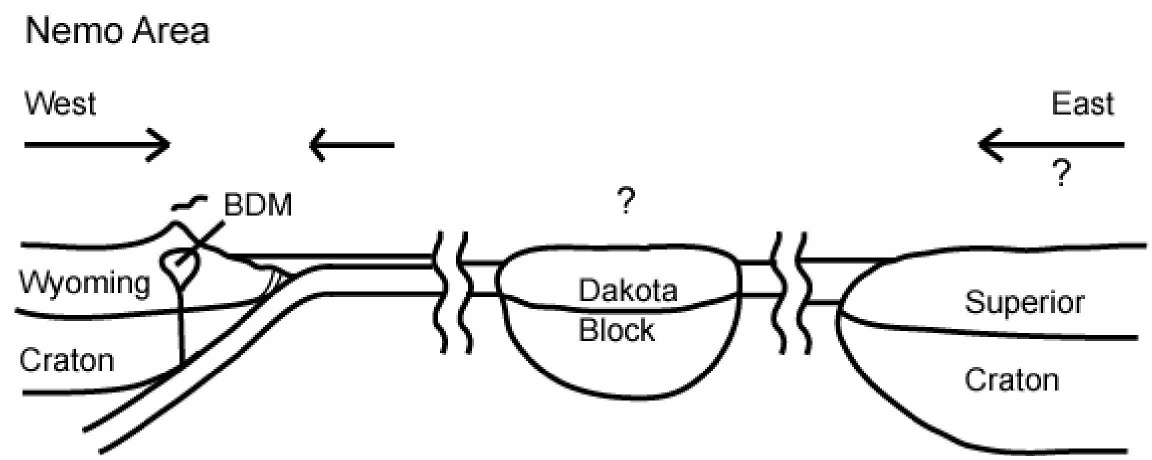

Figure 5.1 Tectonic model for the formation of the BDM at 2.48 Ga in association with subduction of oceanic lithosphere beneath the Wyoming Craton.

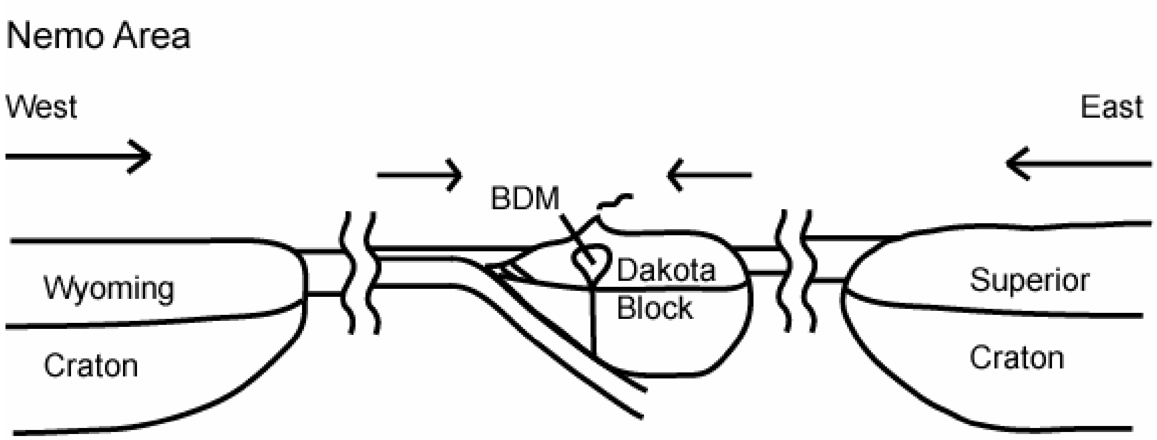

Figure 5.2 Tectonic model for the formation of the BDM at 2.48 Ga in association with subduction of oceanic lithosphere beneath the Dakota Block.

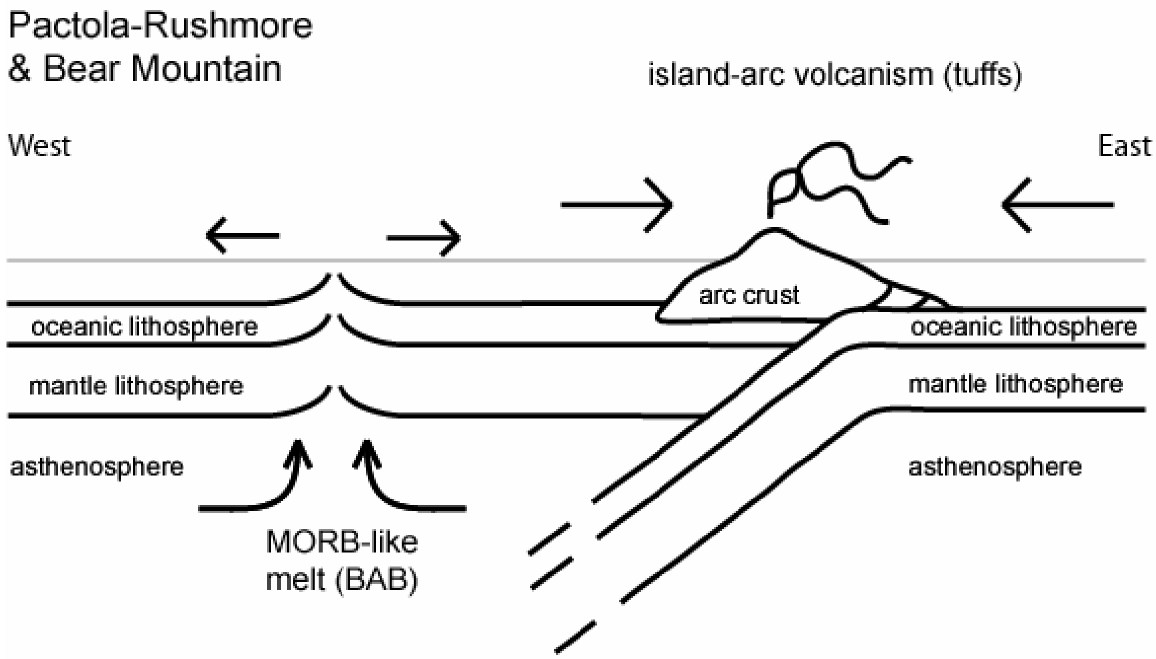

Figure 5.3 Tectonic model for the formation of the island-arc tholeiites and MORB-like basalts in a back-arc basin at Pactola-Rushmore (age = ~1.88 Ga) and at Bear Mountain (age = ?). MORB signatures are attributed to back-arc extensional volcanism.

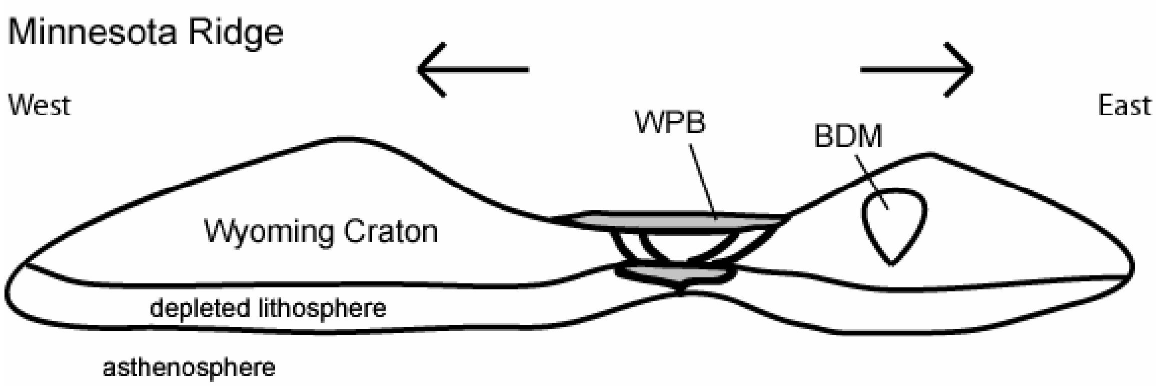

Figure 5.4 Tectonic model for the formation of the within-plate basalts (WPB) at Minnesota Ridge (age = ~1.88 Ga) by partial melting of a depleted lithospheric mantle. BDM shown on eastern block for spatial reference.

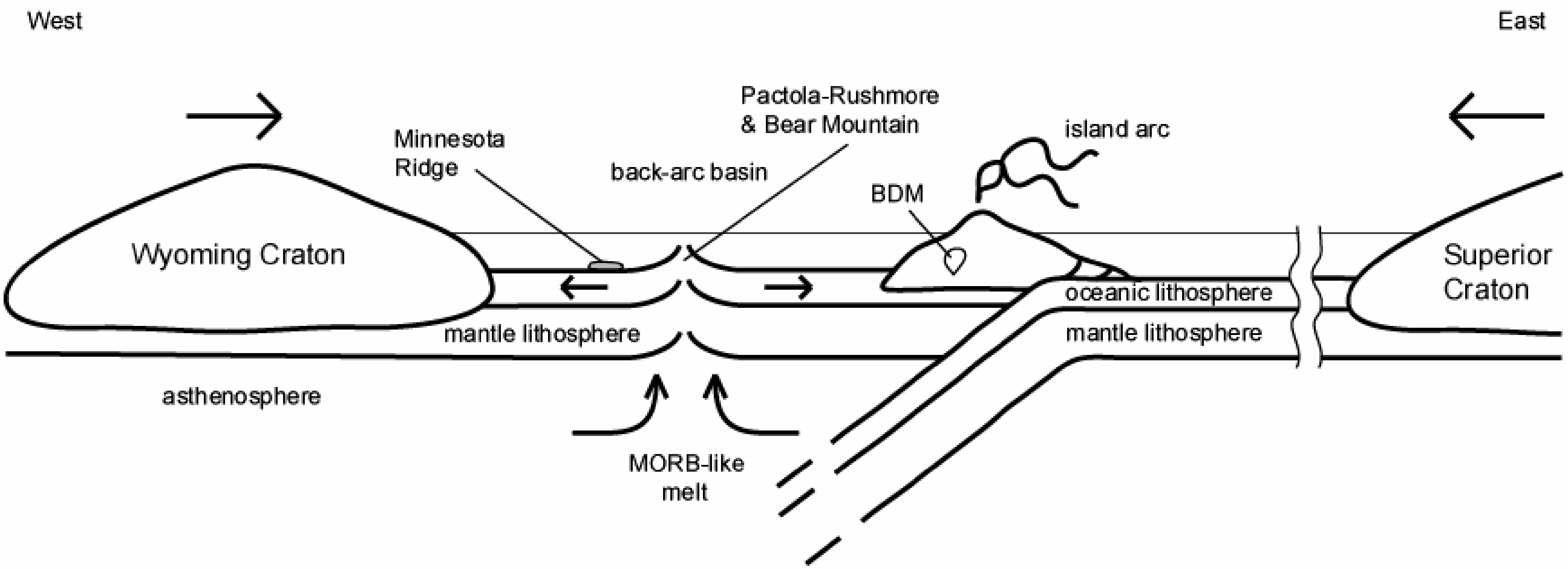

Figure 5.5 Tectonic model for the four mafic suites in the Black Hills with at ~1.88 Ga. In this model the BDM (age = 2.48 Ga) is part of a block that was rifted off of the Wyoming craton after formation, and with the innitiation of a rift that formed the basalts at Minnesota Ridge. The subduction of oceanic lithosphere beneath the rifted block formed an island arc with associated back-arc basin, where the basalts at Pactola-Rushmore and Bear Mountain were formed. The Superior Craton is shown at some distance to the east, which eventually collided during the BHO ~1.75 Ga.

6 Conclusions

The geochemistries of the mafic suites in the Black Hills reveal much about the tectonic history of the Black Hills, a subject that is widely debated and until now poorly understood. The tectonic implications, particularly for the Blue Draw Metagabbro, offer a new tectonic environment of formation, which may be in better agreement with the calc-alkaline composition of the nearby Little Elk granite and gneiss. The compositions of the other suites support previous interpretations that the suites are related to rifting, but place the rifting in the context of a nearby volcanic arc which may have been the source for presumably coeval tuffs. However, without accurate age constraints on the three suites, it is difficult to ascertain a clear picture of the tectonic evolution of the Black Hills prior to the Black Hills orogeny. Nevertheless, the geochemistry reveals a potential link between the Pactola-Rushmore and Bear Mountain basalts, as well as to the chemically enigmatic basalts at Minnesota Ridge. It is evident that, in order to gain a better understanding of the pre-collisional history of the Black Hills, more work must be done, particularly in determining accurate ages for the mafic rocks. However, the tectonic interpretations in this study provide deeper insights into the Black Hills' geologic history prior to the Black Hills orogenic collision.

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