STRUCTURAL GEOLOGY AND TECTONICS OF THE PALEOPROTEROZOIC ROCKS OF THE MOUNT RUSHMORE QUADRANGLE, BLACK HILLS, SOUTH DAKOTA

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Doctor of Philosophy

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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 dissertation entitled

Structural Geology and Tectonics of the Paleoproterozoic Rocks of the Mount Rushmore quadrangle Black Hills, South Dakota

Presented by Joseph Christopher Hill

A candidate for the degree of Doctor of Philosophy in Geological Sciences

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

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To my son,

Aidan Christopher

You gave me the reason to persevere…

And my wife,

Kristin Leigh

You gave me the strength.

Nothing is so firmly believed as what we least know.

- Michel de Montaigne

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ABSTRACT

The Paleoproterozoic assembly of Laurentia, the cratonic core of North America, involved the assembly of numerous Archean microcontinents, between ~ 1.96 to 1.70 Ga, and continued with the accretion of island arc terranes until about 1.63 Ga. The Black Hills, South Dakota lie along the eastern margin of the Wyoming Archean craton, one of the assembled Archean microcontinents, and the western edge of the southern projection of the Paleoproterozoic Trans-Hudson orogen (THO), which formed as a result of the collision of the Superior Archean craton and Archean cratons to the west. Most of the southern THO is covered by a thick sequence of Phanerozoic sedimentary rocks; however, the Black Hills contain an exposed core of Precambrian rocks that are critical to our understanding of large-scale and complex aspects of the assembly of southern Laurentia.

The Precambrian rocks of the Black Hills uplift record multiple deformational and metamorphic events related to three orogenic events that have affected the study area: (1) the ~1780 Ma Black Hills orogeny, (2) the ~ 1720 Ma Dakotan orogeny, and (3) the ~1690 Ma Central Plains orogeny. In response to these three orogenies, the rocks of the Mount Rushmore quadrangle, which are the focus of this study, have undergone a complex Paleoproterozoic history of ductile folding, intrusion of the Harney Peak granite (HPG)(ca. 1715 Ma), and two period of metamorphism.

The study area was divided into nine fault-bounded blocks that have different structural histories and were, therefore, evaluated as distinct structural domains. A major structural discontinuity defined by the Keystone and Empire Mine faults separates six of the structural domains, to the east of the discontinuity, from three structural domains to the west. Evidence from detailed mapping demonstrates that this discontinuity is a sinistral strike-slip fault zone that truncates all earlier structures to the southwest. The domains to the west of the discontinuity are proximal to the NE margin of the HPG but differ considerably in their response to the emplacement of the HPG. The domains to the east of the discontinuity are interpreted as being part of an allochthonous group of fault blocks with an overall sense of sinistral displacement. The allochthonous blocks northeast of the mapped discontinuity are believed to represent a series of "tectonic slivers" that moved unknown distances along the eastern margin of the Archean Wyoming craton.

Structural features mapped in the study area and the overall structural trends of the east-central Black Hills may be best explained by an oblique convergence model involving oblique collision of an intervening continental fragment, the Dakota block, during terminal Wyoming-Superior collision. This collision resulted in early east-west convergence that produced the earliest folds, faults, and metamorphism recognized in the Black Hills. During the later stages of collision, the overall convergence became more northwest directed, resulting in the strong overprint of NW-trending folds and fabrics. The series of anastomosing strike-slip faults evident in the east-central Black Hills were formed as a result of

sinistral transpression when the Dakota block slipped along the eastern margin of Wyoming craton.

Emplacement of the Harney Peak Granite and the associated second prograde metamorphic event occurred during the waning stages deformation as dilatational space was created in a releasing bend during north directed transpression. Uplift of the fault-bounded block containing the Harney Peak Granite is likely a result of differential buoyancy related to the emplacement of the melt coupled with late compression of the releasing bend reactivating the faults in high-angle reverse motion. Movement along strike-slip faults continued after the emplacement of the Harney Peak Granite. A late deformational event affects the southern half of the study area and is likely a result of far-field stresses related to the Central Plains orogen ~ 1690 Ma.

INTRODUCTION

The assembly of Laurentia, the cratonic core of North America, was initiated during Early Proterozoic time by the assembly of numerous Archean microcontinents, between ~ 1.96 to 1.81 Ga, and continued with the accretion of island arc terranes until about 1.63 Ga (Hoffman, 1988). As a result of this process, Laurentia is composed of a network of Early Proterozoic orogenic belts, accreted island arc terranes, and formerly independent Archean microcontinents with highly deformed margins (Hoffman, 1988) (Figure 1). These elements have remained coherent and relatively rigid for at least the last one billion years. However, the nature and timing of many of the Paleoproterozoic events involved in the assembly of Laurentia remain poorly understood. The keys to a better understanding of this process lie in unraveling the complex deformation and thermal events produced along the collisional boundaries of the various assembled components of Laurentia.

The Black Hills of South Dakota lie along the eastern margin of the Archean Wyoming craton, one of the assembled Archean microcontinents, and the western edge of the southern projection of the Early Proterozoic Trans-Hudson orogen (Figure 2). They contain the only significant exposures of Precambrian rocks in a region where most Precambrian units are covered by a thick sequence of Phanerozoic sedimentary rocks. As a result, the Black Hills contain Precambrian rock exposures that are critical to our understanding of large-scale and complex aspects of the assembly of southern Laurentia, and they
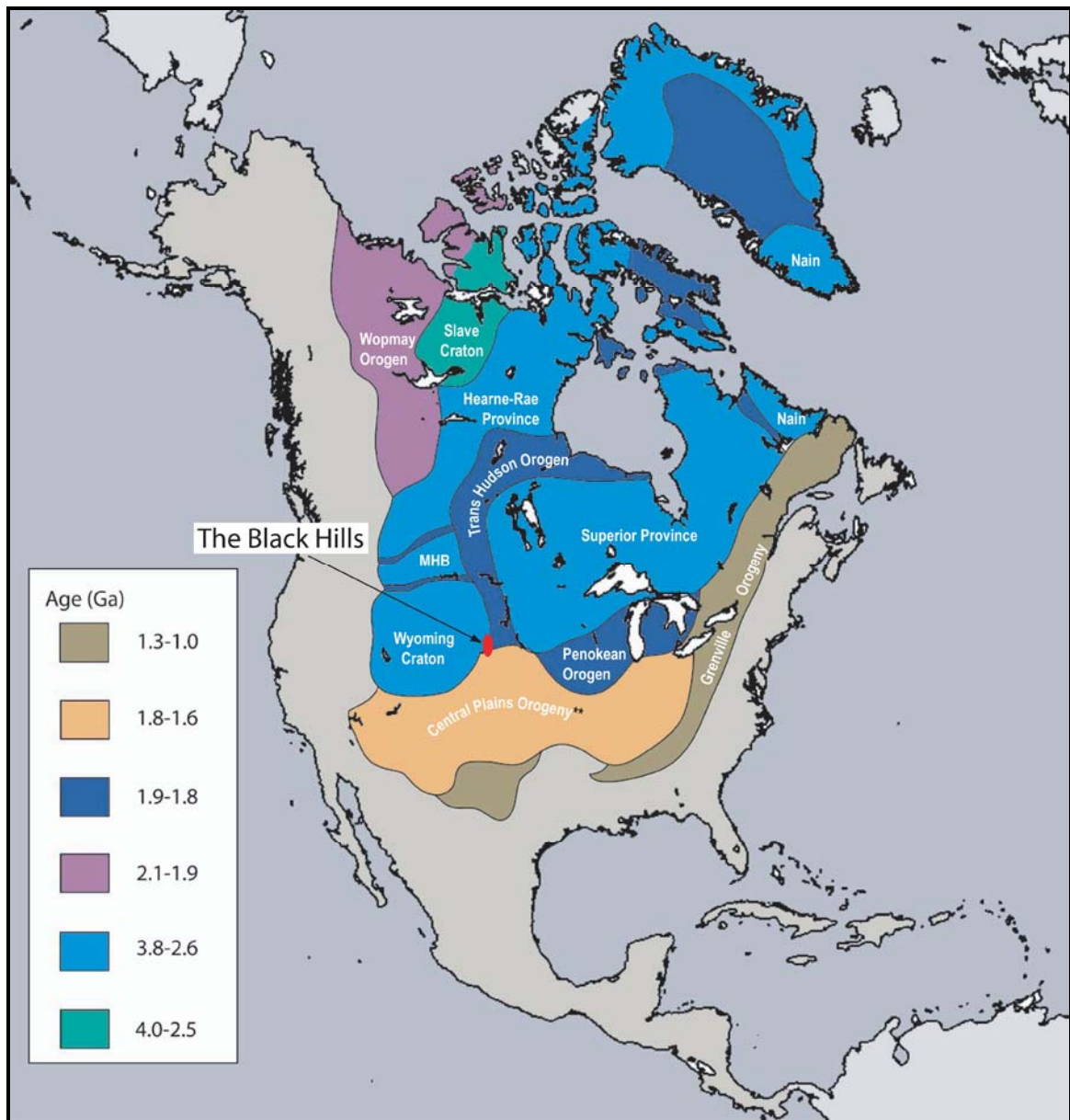
Figure 1 - Precambrian tectonic elements of Laurentia relative to modern North America. Archean microcontinents include the Slave craton, Hearne-Rae province, Wyoming craton, Superior craton, Medicine Hat block (MHB). Darker blue represents Paleoproterozoic orogenic events. See text for more discussion. Modified from Hoffman (1988). Not labeled on map are the Thelon Orogen (Slave/Hearne-Rae collision), Vulcan Tectonic zone (MHB northern boundary), Great Falls Tectonic Zone (MHB southern boundary), and the Torngat Orogen (Nain/Superior collision).
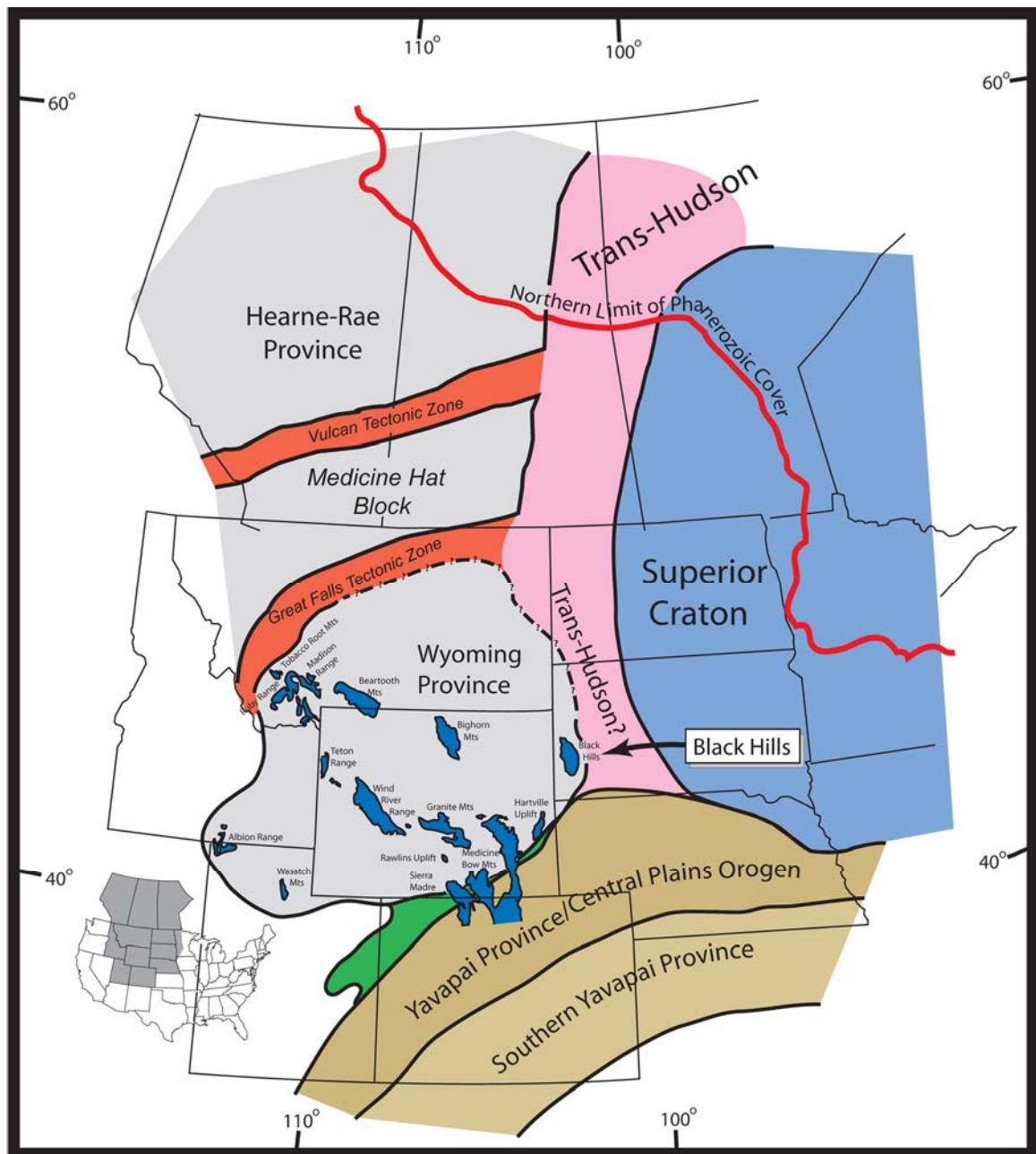
Figure 2 - Tectonic setting and location of the Black Hills uplift showing the major tectonic elements of the mid-continent region of North America. Note the Laramide basement cored uplifts (dark blue) that define the Wyoming Province. The Cheyenne Belt/Green Mountain block is shown in green. The southern Yavapai province marks the boundary of 1.7 Ga basement. Modified from Karlstrom et al. (2002).

offer a unique opportunity to study part of the 1900 Ma to 1600 Ma Paleoproterozoic orogenic events involved in this assembly. Specifically, the Black Hills offer the only surface exposure, south of 54° N latitude, of the deformed belt of Archean and Paleoproterozoic rocks in the collisional zone between the Archean Wyoming and Superior provinces.

Based largely on seismic reflection and refraction (e.g. Baird et al., 1995, 1996; Lucas et al., 1993, 1994; Nelson et al., 1993; White et al., 1994; Latham et al., 1988), magnetotelluric (e.g., Jones et al., 1993, 1995; Garcia and Jones, 2005), electromagnetic (e.g. Jones et al., 2005 and references therein; Toft et al., 1993), geomagnetic depth sounding (e.g., Jones et al., 2005; Camfield and Gough, 1977; Camfield et al., 1970), paleomagnetic (e.g., Stauffer, 1984) and gravity (e.g. Klasner and King, 1986, 1990) geophysical evidence, this collisional zone has been broadly interpreted to be a southern extension of the Trans-Hudson orogeny that was truncated by a collage of island-arc terranes of the ca. 1680 Ma Central Plains orogen (Klasner and King, 1990) (Figure 2). However, differences between the Trans-Hudson events recorded in Canada (1850 - 1800 Ma; Bickford et al., 1990) and events recorded in the Black Hills (1775 – 1690 Ma; Dahl et al., 2005a,b) allows for multiple hypotheses regarding the assemblage of southern Laurentia. The Canadian Trans-Hudson is a collage of mainly juvenile, arc-related Paleoproterozoic domains, oceanic lithosphere, associated intra-oceanic deposits, and the deformed margins of formerly independent Archean microcontinents (e.g., Bickford et al., 1990; Hoffman, 1988). In contrast, the Black Hills are dominated by rift-related metamorphosed

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supracrustal rocks (Dahl et al., 2005a,b; Redden et al., 1990; Dutch and Nelson, 1990; Gosselin et al., 1988).

The broad objective of this research is to provide data and analysis to further constrain the nature of the Early Proterozoic collision between the Wyoming and Superior Archean cratons and the island arc terranes of the Central Plains orogen.

Importance of the Mount Rushmore Quadrangle as a Proxy for Understanding the Tectonics of the Black Hills

The Black Hills were uplifted during the 75-35 Ma Laramide Orogeny and expose a ~110 x 70 km portion of the buried Proterozoic collisional zone between the Wyoming and Superior provinces (Lisenbee, 1978; Bird, 1998). The Precambrian rocks of the uplift record multiple deformational and metamorphic events related to the assembly of southern Laurentia (e.g., Redden et al., 1990; Dahl et al., 1999b, 2005a,b). The Paleoproterozoic rocks have a complex sedimentary sequence and, in general, consist of basal metaconglomerates and quartzites nonconformably overlain by various quartzites, metagraywackes, iron formations, metavolcanics (tuffs, basalts), gabbros, mica schists, phyllites, and slates. The Precambrian rocks were affected by at least three deformational events (this study), although as many as five have been suggested (e.g. Redden et al., 1990), that resulted in multiple episodes of faulting and folding. Two episodes of prograde metamorphism and one regional-scale intrusive event are also recorded in the Paleoproterozoic rocks.

The Mount Rushmore quadrangle was chosen because of its complexity and geologically critical location. The rocks of the quadrangle have undergone a particularly complex history of Paleoproterozoic ductile folding, granite intrusion, and metamorphism, including multiple deformational and metamorphic events. Numerous faults, intrusions, and folding events are evident on existing large-scale maps of the area (cf. Dewitt et al., 1989) and these attest to a complex history of Proterozoic deformation. Three orogenic events have affected the study area: (1) the ~1780 Ma Black Hills orogeny (Dahl and Frei, 1998; Goldich et al., 1966), (2) the ~ 1720 Ma Dakotan orogeny (Chamberlain et al., 2002), and (3) the ~1690 Ma Central Plains orogen (Sims and Peterman, 1986). The earliest metamorphic event affected all Paleoproterozoic rocks of the Black Hills and is temporally associated with the Black Hills orogeny. This event was later overprinted by the thermal aureole of the Harney Peak intrusion at ~1715 Ma (Norton and Redden, 1990; Dahl et al., 1999a). The Mt. Rushmore quadrangle includes the northeastern contact of the Harney Peak Granite and a significant portion of its metamorphic aureole. The Harney Peak granite intrusion played a key role in syn-tectonic deformation and associated metamorphism in the Black Hills. Understanding the metamorphic and fabric relationships in the southern Black Hills is essential to developing a coherent tectonic model for the Black Hills, which is, in turn, critical to understanding the assembly of southern Laurentia.

The Mount Rushmore quadrangle is located approximately 25 kilometers (15 miles) west-southwest of Rapid City and encompasses an area of roughly

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225 km^2 (Figure 3). It includes features formed during many of these events, and metasedimentary, metavolcanic, and mafic igneous rocks, of the area record pre-, syn-, and post-intrusional fabrics and features that were reoriented along the northeast contact of the Harney Peak Granite intrusion (Figure 4). The
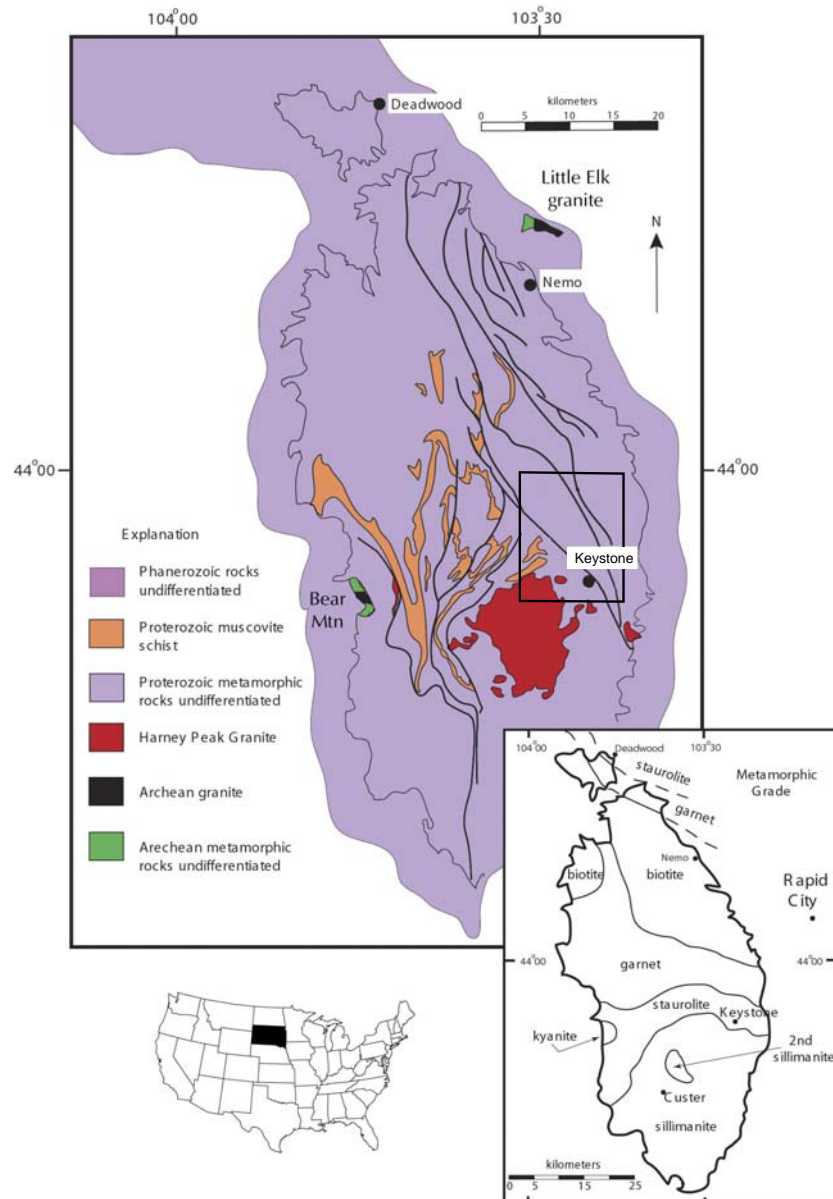
Figure 3 - Location and generalized geologic map of the Precambrian Black Hills. Modified from Redden and Lisenbee (1996). Black rectangle indicates approximate outline of the study area.

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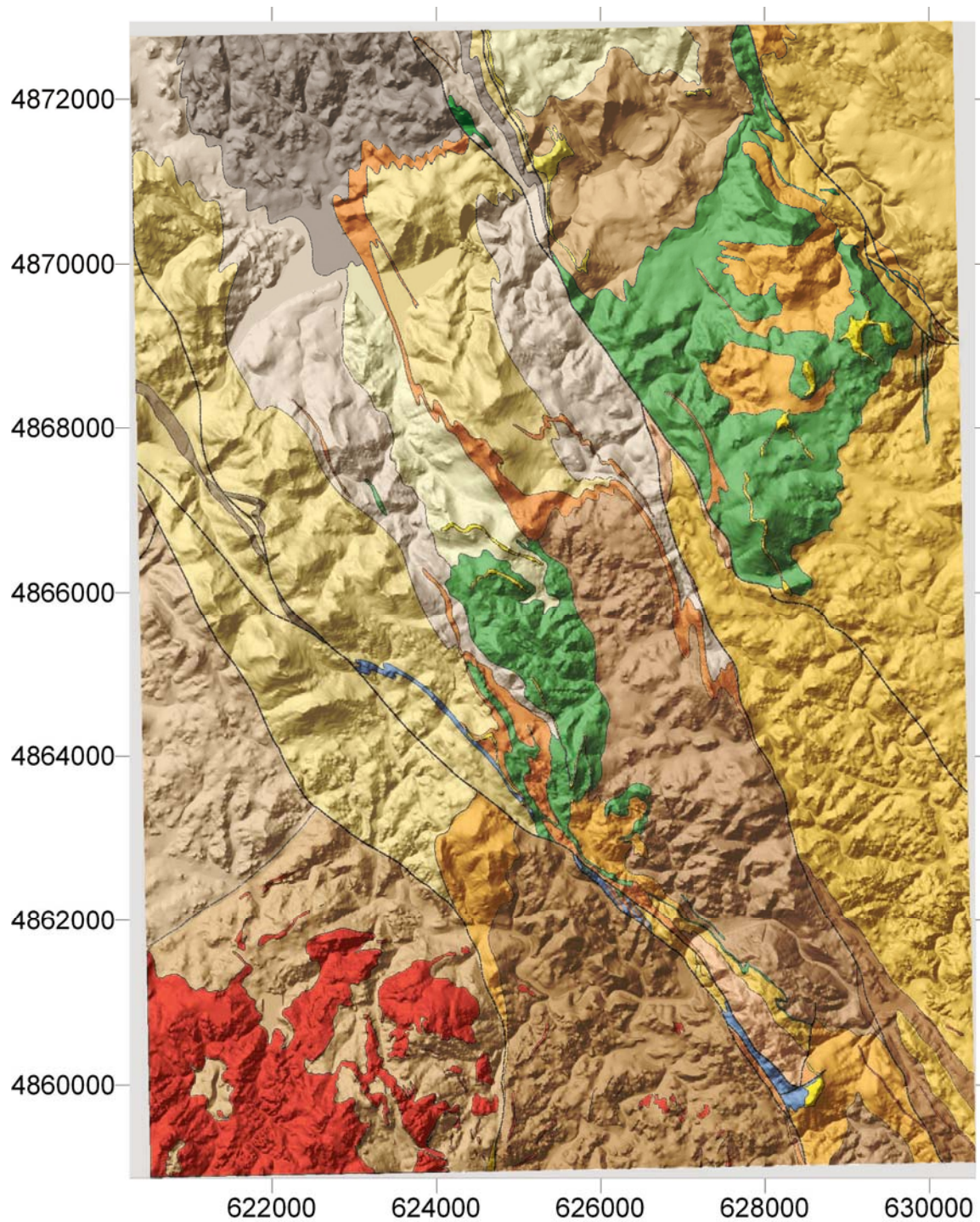
Figure 4 - Geologic map of the Mount Rushmore 7.5-minute quadrangle produced during this study. Geology is draped on the 1:24,000 scale DEM model for the quadrangle. Coordinates in UTM NAD 27. Note the outcrop pattern of the Harney Peak Granite (red) and the general north-northwest trend of major faults (bold black lines). See Plate I for more detailed geologic map.

incongruity of structural features and metamorphism related to the Harney Peak Granite across fault-bounded blocks within the Mt. Rushmore quadrangle suggests a two-phase, protracted single orogenic event along the eastern margin of the Wyoming Province that encompasses both the Black Hills and Dakotan orogenies. Thus, the study area offers the best opportunity to unravel the complex stratigraphic, metamorphic, and structural relationships in the east-central Black Hills and elucidate the tectonic history of the Black Hills.

Research Objectives

The general objective of this study was the resolution of the metamorphic, stratigraphic, and structural relationships in the Mount Rushmore quadrangle, with the primary focus on the relationship between multiple deformational fabrics and multiple metamorphic events. The overarching goal of this work was to help elucidate the tectonic history of the Black Hills. The specific objectives of the research were to: (1) map the distribution of the major lithologic units; (2) provide information on stratigraphic relationships within the study area; (3) identify and quantify the geometry of major folding and faulting events; (4) identify and measure the orientation of the principal deformation fabrics and determine their relationships to each other, to metamorphic porphyroblast growth, and to regional structural, and tectonic events; and (5) assess the role of the Harney Peak Granite in the deformational and metamorphic history of the region. These data are used to evaluate the degree to which correlations of structural features, deformation fabrics, and rock units can be made across multiple fault-bounded

blocks that make up the study area and to investigate the implications that such correlations have for the overall tectonic development of the Black Hills. This research provides data and analysis to assess geologic and tectonic interpretations of the Proterozoic deformation in the Black Hills and the assembly of southern Laurentia.

Regional Geologic Setting

The Precambrian core of the Black Hills has been variously interpreted to reveal a series of ensialic, epicratonic, and/or back-arc rift basins floored by Archean basement rocks of the Wyoming (?) province infilled by Early Proterozoic clastic sedimentary, volcaniclastic, and mafic igneous rocks (e.g., Gosselin et al., 1988; Redden et al., 1990; Redden and Dewitt, 1996). The diverse tectonic interpretations demonstrate the imprecise and limited nature of the current data base relating to the Black Hills. These rocks experienced at least three episodes of penetrative deformation and two episodes of prograde metamorphism from ~1780 – 1690 Ma. A late period of regional unroofing began at ~1500 Ma (Holm et al., 1997). By the beginning of Cambrian time, the Proterozoic rocks were unroofed and eroded close to their present structural level (Lisenbee and Dewitt, 1993). During the Phanerozoic, the Paleoproterozoic rocks were non-conformably overlain by a series of clastic and carbonate sedimentary rocks (Lisenbee, 1978; Bird, 1998). During the Laramide orogeny, area was subjected to large-scale doming that created the Black Hills and re-exposed the core of the crystalline Precambrian complex.

Archean Basement

The oldest rocks in the Black Hills are Archean in age and consist of two small exposures, one at Bear Mountain (Bear Mountain Granite, 2563 ± 6 Ma; McCombs et al., 2003), along the western edge of exposed Precambrian rocks, and the other (Little Elk Granite, 2559 ± 6 Ma; McCombs et al., 2003) along the northeastern edge of the Precambrian core (Figure 3). The Little Elk Granite is a medium- to coarse-grained, porphyroblastic, I-type granite gneiss that intruded a supracrustal sequence of Archean biotite-feldspar gneiss (Gosselin et al., 1990). The Archean biotite feldspar gneiss records a bedding parallel, east-northeast trending, penetrative foliation that the intruded granitic gneiss does not, and thus records the oldest deformation observed in the Black Hills (Gosselin et al., 1988). Both the granite and the surrounding metasedimentary rocks have a dominant northwest-trending foliation that crosscuts an older east-northeast-trending foliation in the surrounding biotite gneisses (Gosselin et al., 1990; Redden et al., 1990). The contact between Archean rocks of the Little Elk terrane and Paleoproterozoic rocks has been interpreted as a fault (Gosselin et al., 1988) or an angular unconformity (Jack Redden, *pers. comm. in* Gosselin et al., 1988). The slightly older Bear Mountain Granite is a medium-grained to pegmatitic, peraluminous, leucocratic, S-type granite that closely resembles the much younger Harney Peak Granite (Gosselin et al., 1988, 1990; Redden et al., 1990). The dominant structural element in the Bear Mountain Granite is a variably developed northwest-trending foliation (Gosselin et al., 1990). The Bear Mountain Granite occurs as concordant, massive to foliated, sill-like bodies that

were intruded into bedded quartz-feldspar-biotite schists (Redden et al., 1990). The schists are overlain by a thin, discontinuous metaconglomerate that contains granite and feldspar pebbles, therefore the immediately enveloping quartz-biotite schists are interpreted to be Archean while the metaconglomerate is interpreted to be Proterozoic (Redden et al., 1990). Gosselin et al. (1988) report an east-northeast trending, bedding parallel foliation in a couple of outcrops (Gosselin et al., 1988; Redden et al., 1990), but it is not clear whether they occur in the Archean rocks or overlying Paleoproterozoic rocks. Dahl et al. (2005a,b) report a relict east-northeast trending fabric in garnets from a single sample (PR-1; Dahl and Frei, 1998; Dahl et al., 2005a,b) of the Paleoproterozoic metasedimentary rocks that surround Bear Mountain. From this, I infer that the east-northeast trending fabric in the Bear Mountain terrane is restricted to the Paleoproterozoic succession. Therefore, the east-northeast foliation observed at Bear Mountain is younger than a similarly oriented penetrative deformation in the Archean rocks of the Little Elk terrane. The fabrics represent two distinct penetrative deformational events. The origin of the fabric observed in the Archean Little Elk terrane is unknown while the fabric recorded in the Paleoproterozoic rocks surrounding the Bear Mountain terrane has been related to cryptic tectonism between ca. 2170 and ca. 1960 Ma (Redden et al., 1990) or early stages of the Central Plains orogen (Dahl et al., 2005a,b).

Metasedimentary rocks of Archean age do crop out within the Precambrian core of the Black Hills (Gossellin et al., 1988; Redden et al., 1990). Archean metasedimentary rocks are restricted to occurrences immediately

adjacent to Archean granites (Redden et al., 1990). Metasedimentary rocks of known Archean age are practically indistinguishable from younger Proterozoic metasedimentary rocks, leaving open the possibility that unrecognized Archean sediments may occur elsewhere in the crystalline core of the Black Hills.

Paleoproterozoic Rocks

The Precambrian igneous and metamorphic rocks that are now exposed in the Black Hills have been interpreted to be primarily of Paleoproterozic age and have been divided into two broad age categories: (1) an older, ~2550 – 2480 Ma rift related sequence (Redden, 1981; Dahl et al., 2005a,b) that is unconformably overlain by (2) younger ~2015 – 1885 Ma (Bekker et al, 2003: Dahl et al., 2005a,b) continental shelf-rise, shallow-water deposits (Redden et al., 1990). At least two unconformities have been identified in the metasedimentary sequence (Redden et al., 1990). Most of the Paleoproterozoic metasedimentary rocks lack precise age constraints. In general, the Paleoproterozoic rocks consist of basal metaconglomerates and quartzites nonconformably overlain by various quartzites, metagraywackes, iron formations, metavolcanics (tuffs, basalts), gabbros, mica schists, phyllites, and slates.

~2550 – 2480 Ma Rift Succession

The oldest Proterozoic rocks are exposed in the Little Elk terrane and are described as basal quartz-pebble conglomerates of the Boxelder Creek Formation (Redden, 1981; Gosselin et al., 1988; Redden et al., 1990). The

thickness of the Boxelder Creek was estimated to be >3300 m. The contact

between the Archean and Paleoproterozoic rocks in the Little Elk terrane has

been interpreted to be unconformable or faulted (Gosselin et al., 1988). The

Boxelder Creek Formation is interpreted to represent the older (pre-2480 Ma)

predominately non-marine, rift succession (Dahl et al., 2003, 2005a,b; Redden,

1981) and is restricted to the immediate area adjacent to the Little Elk Granite

and the Nemo area (Figure 3). It is described as a basal assemblage of chloritic

metaconglomerate, metamorphosed fanglomerate, taconite meta-conglomerate,

and chloritic quartzite with pronounced lateral facies changes to phyllite and

dolomitic marble overlain by fluvial metaconglomerate, quartzite, and oxide-

facies iron-formation. An angular unconformity marks the top of this sequence

(Redden, 1981; Redden et al., 1990).

The oldest Proterozoic intrusive rocks (e.g., Blue Draw Metagabbro) have

a reported age of ~2480 Ma (Dahl et al., 2003) and predate the earliest

deformation recorded by the Paleoproterozoic metasedimentary rocks (Redden

et al., 1990). The Blue Draw Metagabbro occurs in the upper part of the

Boxelder Creek Formation, and therefore the age represents the minimum oldest

age of the Proterozoic sequence.

One period of folding predates the unconformity marking the top of the

older rift succession but after the emplacement of the Blue Draw Metagabbro,

bracketing a deformational event occurring in the older succession between

~2480 Ma and ~1985 Ma. This deformation is not recorded in the

Paleoproterozoic rocks of the Bear Mountain terrane. Dahl et al. (2003)

attributed this early deformation to the incipient breakup of the proposed

supercontinent Kenorland.

~2015-1885 Ma Continental Slope-Rise Type Succession

The younger Paleoproterozoic succession nonconformably overlies the

older rift-related succession (Redden et al., 1990; Dahl et al., 2003) and is more

areally extensive. This younger succession dominates the exposed Precambrian

metasedimentary rocks. Redden et al. (1990) subdivided the succession into two

sequences based on inferred age relationships. The older sequence is

composed of shallow-water clastic and carbonate rocks, overlain by tholeiitic

metabasalts, slates, and phyllites (Redden et al., 1990). The younger sequence

consists primarily of turbidite deposits, metagraywackes, shales, and

volcaniclastic rocks in the central and southwestern Black Hills and

metaconglomerates, debris flows, metabasalts, metavolcanics, iron formations,

and quartzites in the east-central Black Hills (Redden et al., 1990).

The complicated faulting and folding, facies changes, spatial distribution

and abundance of similar rock types across the Black Hills combined with the

lack of precise age constraints and paucity of good stratigraphic marker units

makes stratigraphic relationships across the entire Black Hills tenuous.

1715 Ma Harney Peak Granite

The youngest Precambrian rock in the Black Hills is the Harney Peak

Granite (Figure 3). The Harney Peak Granite intruded the younger continental

slope-rise succession at ~1715 $\pm$ 3 Ma (U-Pb monazite; Redden et al., 1990).

The Harney Peak Granite is a heterogeneous, peraluminous, leucogranite

consisting of an inner, biotite-rich, low-^{TM18}O granite, surrounded by a ring of

tourmaline-rich, high-^{TM18}O granite (Nabelek et al., 1992a). Walker et al. (1986)

conducted a Sm-Nd isotope study that demonstrated that the metasedimentary

rocks surrounding the Harney Peak Granite could not be its only source, and

suggested a mixed Archean and Proterozoic source. Nabelek et al. (1992b)

determined that the variations in mineralogy and geochemistry of the Harney

Peak Granite are the consequence of source regions rather than post-

emplacement differentiation. They concluded that the inner, biotite-rich granite

had an immature biotite-rich Archean metasedimentary source, whereas the

outer, tourmaline-rich granite was derived from structurally higher,

Paleoproterozoic muscovite-rich schists.

Deformation and Metamorphism

Three deformational events dominate the Precambrian Black Hills,

although as many as five events have been suggested (e.g. Redden et al., 1990;

Holm et al., 1997; Dahl, 1999a). The relative timing of the deformational events

is still under considerable debate (e.g., Dahl et al., 2005a,b; McCombs et al.,

2004; Chamberlain et al., 2002). The earliest deformation event is only

recognized in the Archean Little Elk terrane and consists of a cryptic east-

northeast foliation (Gosselin et al., 1988). This deformational event did not affect

the Paleoproterozoic rocks in the Black Hills, and therefore it is inferred to be

Archean. The Little Elk Granite terrane also records the earliest metamorphic events exposed in the Black Hills given that the oldest rocks are both gneisses. The subsequent Proterozoic deformational events are the focus of this study.

Two metamorphic events are recorded in the Paleoproterozoic rocks of the Black Hills, with the highest metamorphic grade reaching the second sillimanite zone southwest of the Harney Peak Granite (Figure 3; Helms and Labotka, 1991). After the deposition of the supracrustal sequences (ca. 1880 Ma; Dahl et al., 1999a), but prior to the intrusion of the Harney Peak Granite (~1715 Ma), the Black Hills region underwent at least upper greenschist facies regional metamorphism (M_1). The age of this metamorphic event has been broadly interpreted to be between 1880 Ma and 1750 Ma (e.g., Redden and Dewitt, 1996; Redden et al., 1990; Dahl et al., 1999a, b). The M_1 event has been attributed to collision of the Wyoming and Superior provinces (Dewitt et al., 1986, 1989; Redden et al., 1990; Terry and Friberg, 1990; Dahl et al., 2005a,b). I has been commonly reported in the olderliterature as having occurred at ca. 1840 Ma based on a whole-rock Rb/Sr "disturbed isochron" date obtained by Zartman and Stern (1967). However, reset whole-rock Rb/Sr data are highly suspect because of limits of strontium rehomogenization (e.g. Lanphere et al., 1964; Herman et al. 1986; Faure, 1986). Recalculation of this data by Dahl et al. (1999a) yielded an 1800±70 Ma estimate, offering little improvement. Recent Pb-Pb dates of garnets and $^{40}Ar/^{39}Ar$ data from metamorphic rocks suggest 1770-1740 Ma metamorphism for the regional M_1 event (Dahl et al., 1999a, 1999b, 2000). Although the more precise timing of this event has been unclear, recent chemical

dating of monazite by Dahl et al. (2005 a,b) suggests two episodes, the first at ~1780 Ma and the second beginning at 1755 Ma, based on a single metapelite sample from the Bear Mountain area. The 1780 Ma age is similar to dates reported in the Hartville uplift to the southwest of the Black Hills and has been recently attributed to a "Black Hills orogeny," with the younger ages ascribed to a "Dakota orogeny" (Chamberlain et al., 2003).

The M_2 event (~1715 Ma; U-Pb monazite age) is associated with the emplacement of the Harney Peak Granite and hundreds of associated granitic dikes and pegmatites (Norton and Redden, 1990). As such, the M_2 event can be thought of, with respect to the area of exposed Precambrian rocks in the Black Hills, as a regional-contact event. The leucogranitic melts and pegmatites associated with the M_2 event are interpreted to have intruded relatively cool ($<500^o$ C) country rocks (Holm et al., 1997), overprinting the regional M_1 metamorphism throughout the central crystalline core of the Black Hills. Nabelek et al. (*in press*) suggest that the Harney Peak Granite was intruded into a fault-bounded crustal block that was subsequently uplifted to its current structural level. The regional M_1, dominantly garnet-grade, assemblages were overprinted by metamorphism and metasomatism that accompanied intrusion of the Harney Peak Granite.

Tectonic Models

Two different tectonic models have been proposed for late Archean orogenesis along the southeastern margin of the Wyoming Province, to account

for both the presence of the Little Elk and Bear Mountain granites and their weakly developed foliations. Karlstrom and Houston (1984) proposed that an unidentified Archean continental block collided with the Wyoming Province, resulting in a continent-continent collision and creating a coherent continental mass that was later rifted to form the basin(s) into which the majority of the Late Proterozoic metasediments in the Black Hills were deposited. In contrast, Redden et al. (1990) suggested that two episodes of ensialic rifting generated and exposed the Little Elk and Bear Mountain terranes prior to 1964 Ma and led to the development of the Black Hills basin(s). Currently available data and observations are not sufficient to favor either model.

Models of Paleoproterozoic tectonism in the Black Hills are no less controversial. Redden et al. (1990) suggested a tectonic history that included, in order of occurrence: an early compressional event of undetermined orientation, ensialic rifting, NE-SW compression, ensialic rifting, subsidence, E-W compression, subsidence, NW-SE compression (F_1 folding), E-W compression (D_2 event), intrusion of the Harney Peak, and finally NW-SE compression. Klasner and King (1990) developed a tectonic model based on the assumption that the Black Hills are the southern extension of the Trans-Hudson Orogen (THO). New age data (cf. Dahl et al., 1999 a,b; Chamberlain et al., 2002), which are discussed in a subsequent section of this report, suggest that the intervening orogen between the Wyoming and Superior provinces (referred to as the Dakota segment) was formed by a separate orogenic event and therefore calls into question the Klasner and King model. I propose an alternative tectonic model

based on the lack of structural continuity and stratigraphic correlation across the fault boundaries in the study area.

Unresolved Issues of Black Hills Geology

The preceding overview of the regional geology suggests that there are several unresolved questions related to the construction of the Precambrian Black Hills that bear on the broader tectonic history. In particular, (a) it is uncertain that the Black Hills represent a simple collisional terrane of the Trans-Hudson orogeny, and (b) the recent propositions that closely-spaced multiple deformations in time represent multiple orogenies is not consistent with collisional orogens, such as the Himalayas, that are constructed over tens of millions of years. Moreover, the data presented in this study suggest that fault-bounded blocks within the Black Hills may have had different structural, stratigraphic, and tectonic histories. New research (e.g., Nabelek et al., *in press*; this study) is questioning the view that all the rocks of the Precambrian Black Hills were subjected to the same deformational and metamorphic events. Many questions regarding the nature of deformation and the causative events in the Black Hills remain unanswered in sufficient detail. Among the broader questions are: What tectonic event(s) are responsible for the multiple tectonic fabrics observed in the Black Hills? What timing constraints (if any) can be applied to the observed metamorphism and deformational fabrics? What role did the Harney Peak Granite play in regional deformation and metamorphism, or

alternatively, what role did deformation play in emplacement of the granite magmas? Are there unrecognized terrane boundaries in the Black Hills?

Lithotectonic Units versus Stratigraphy

The study area is a prime example of repetition of similar rock units that have complicated structural, metamorphic, and facies relationships that are not easily classified into any determinate stratigraphy. In general, the dominant rock assemblages of Proterozoic age in the study area are (1) pelitic schists, phyllites, and slates; (2) metagraywackes, siliceous mica-schists, and quartzites; (3) metabasites – including basalt, gabbro, and amphibolite; and (4) granite and associated pegmatites. Minor rock assemblages include iron-formations, calcareous phyllites, and calc-silicates.

Structural repetition by folding and faulting, and facies changes within the supracrustal units, make stratigraphic correlations tenuous at best. For example, the Mount Rushmore quadrangle is cut by at least four major north-west trending faults that divide it into nine fault-bounded blocks (Figure 5), each with a potentially different structural history. In general, the fault-blocks contain similar lithologic units but precise correlation between them remains problematic, hence no definitive stratigraphic correlation between rocks of separate fault blocks has been established.

This study relies on grouping rocks into mappable lithostratigraphic sequences within the fault-bounded blocks. The lack of distinct marker units

within the metasedimentary sequences, along with varying degrees of metamorphic overprinting and facies changes, and lack of any age dating techniques applied to the metasedimentary sequence made determination of an actual stratigraphy nearly impossible. Where possible, stratigraphic and structural facing indicators were used to determine stratigraphic younging directions. Correlation with other workers' stratigraphic successions would be, at this time, speculation and has been avoided (cf. Appendix B)

The rocks of the study area have been divided into fourteen lithostratigraphic units. The Harney Peak Granite and related pegmatites are clearly the youngest Precambrian rocks cropping out. Age relationships of other Paleoproterozoic rocks remain equivocal. Similar rock types occur in most of the fault-bounded blocks and have been mapped as similar rock units. This grouping is not intended to imply any stratigraphic correlation between similar lithologies across major faults within the study area. Appendix A lists and describes the lithostratigraphic units used in this study (Table 1). Plate I is the geologic map produced based on these units.
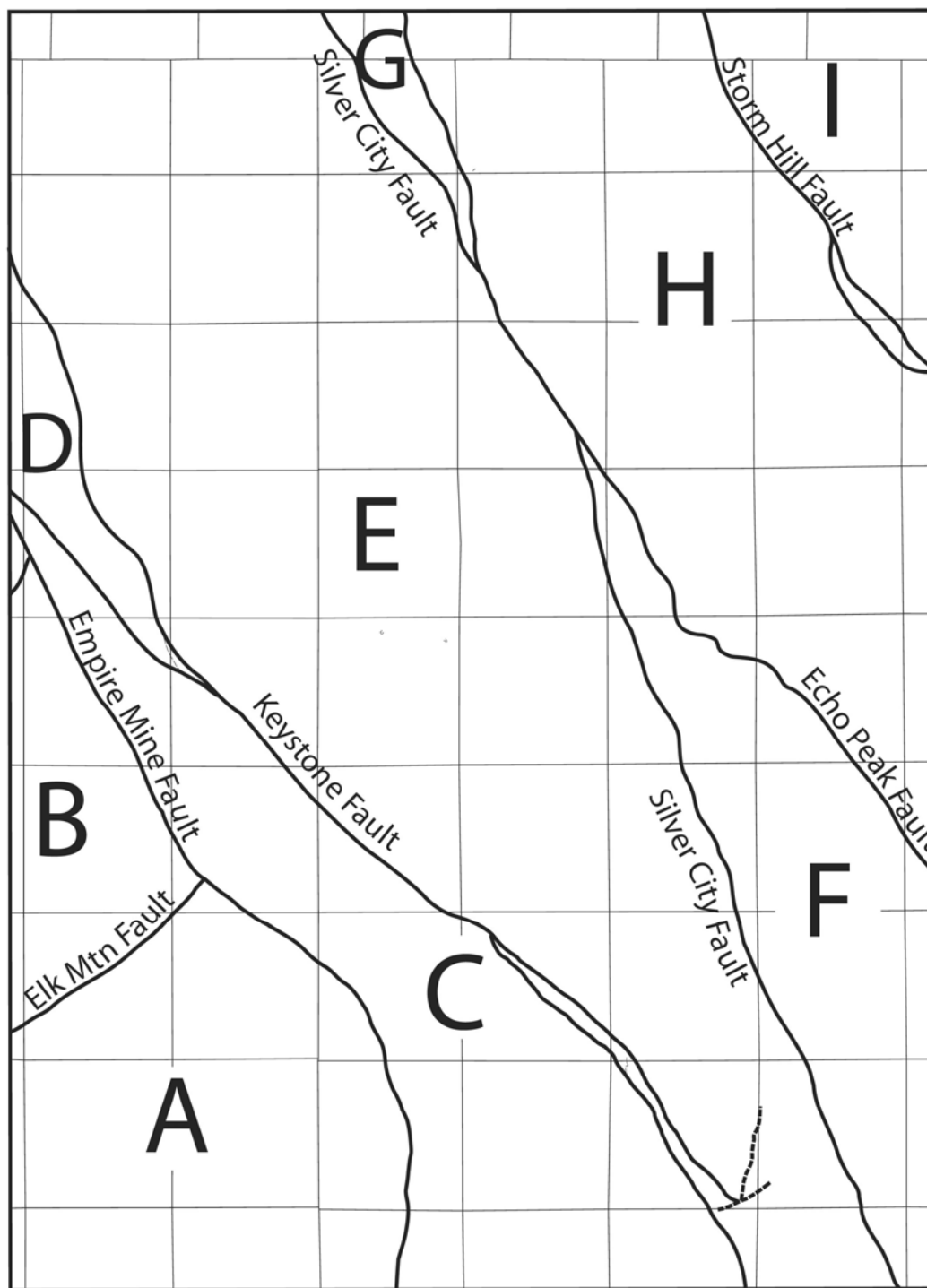
Figure 5 - Outline map of fault bounded blocks delineated during this study in the Mt. Rushmore 7.5-minute quadrangle. Letter designations for fault-blocks will be used throughout this paper. A major structural boundary exists along the northeast side of fault-block C (Keystone Fault) within the study area.

Table 1 - Summary of lithostratigraphic units used in this study. Colors correspond to the map shown in Figure 4. See Plate I and Appendix A for more detailed description.

Problems with Stratigraphic Correlation

One objective of this study was to provide information on stratigraphic relationships within the study area. Many previous structural interpretations in the Black Hills have been based on stratigraphic relationships (Noble and Harder, 1948; Redden 1963, 1968; Ratte and Wayland, 1969; Bayley, 1972b, 1972c; Ratte, 1986), so a significant effort was made to verify stratigraphic interpretations that could potentially be used to assist the structural interpretations of this study. However, for the reasons stated above, stratigraphic correlations are difficult. Available age data are primarily derived from metamorphic porphyroblasts (e.g. garnet, staurolite, monazite) (e.g. Gardner et

al., 1996; Holm et al., 1997; Dahl et al., 1999a, b; Dahl et al., 2003, 2005a,b) that give no information about stratigraphic successions.

In detail, the difficulties in defining and correlating stratigraphic units with any confidence within the crystalline Black Hills are three-fold. The first, and most basic problem, is the recurrence of identical rock types within the succession and the paucity of good stratigraphic marker units. Second, the rocks within the crystalline core have been multiply and complexly deformed. As a result, detailed structural analysis is required to unravel the stratigraphic relationships. Thirdly, the thermal overprint of the Harney Peak Granite has significantly metamorphosed the country rocks within its aureole and the degree of metamorphism is not uniform (Nabelek et al., *in press*).

Locally, and sometimes for some distance in the field, stratigraphic relationships may be determined based on primary structures and distinctive sequences. It is very difficult, however, to correlate these sequences over significant distances due to the structural and metamorphic complexity of the study area and the general similarity of lithostratigraphic units. For example, a turbidite succession at point A may look very similar to another turbidite succession at point B. However, the similarity does not necessarily imply a stratigraphic continuity between the two turbidite successions. Only careful and consistent observation between points A and B will yield a correct interpretation, and only if there is sufficient outcrop to gather the necessary data.

By far, the most consistent primary structure in the study area that provides stratigraphic topping directions is graded bedding, but incomplete

exposure and folding yields reliable younging interpretations only very locally. A large portion of the Mt. Rushmore quadrangle includes turbidite successions that locally preserve incomplete Bouma sequences. Primary bedding features may be recognized in some layers, but the inconsistent nature of preservation of such features between outcrops makes any interpretation of structure based solely on stratigraphic younging criteria suspect.

Previous Stratigraphic Correlations

The stratigraphy of the Paleoproterozoic medisedimentary rocks in the Black Hills remains nebulous. Redden (1963, 1968) reported stratigraphic relationships for metasedimentary rocks in the Fourmile and Berne 7.5-minute quadrangles southwest of the study area. Redden et al. (1990) proffered a rough, first-order correlation of stratigraphic relationships in the Precambrian rocks across the entire Black Hills. However, many of the assertions and correlations of Redden et al. (1990) remain unclear and subject to debate. Previous workers raised concerns about correlating rocks across multiple faults based solely on lithologic similarity (e.g. Ratte and Wayland, 1969; Norton, 1974; Woodland, 1979; Ratte, 1986). Appendix B summarizes some of the major inconsistencies with previous stratigraphic correlations and their application to ascertaining the regional structure.

Methodology

This study was implemented in two phases: (1) a field component and (2) a laboratory component. Detailed mapping began in late May, 2000, and continued through mid-August, 2000. Additional field seasons corresponding to the same time frame were undertaken in 2001 and 2002. Laboratory work was conducted during the intervals between field seasons and continued after the completion of the mapping phase.

Mapping was done at 1:12,000-scale or smaller and compiled at the 1:24,000-scale using USGS digital topographic base maps. Orientation measurements of foliations, fold axial planes and hinge lines, mineral and intersection lineations, and fractures were collected using a Brunton[TM] Model 5005LM Pocket Transit. Locations were recorded in UTM coordinates (1927 North American datum) using a Garmin GPSmap76 hand-held GPS unit equipped with WAAS-differential correction (Wide Area Augmentation System). Typical positional accuracy was better than three meters. Field work involved traverses, generally across regional strike, along all major streams, ridges, roads, and railroads. Additional area-specific traverses were undertaken and spaced closely enough to permit tracing of particular contacts. In addition, "float" was identified and plotted on the map to help delimit contacts.

Structural analyses were aided using the stereographic projection software: GEOrient developed by Professor Rod Holcombe (Department of Earth Sciences, University of Queensland, Australia) and SpheriStat™ version 2.2 from Pangaea Scientific. Laboratory studies involved petrographic and

micro-structural analysis using an Olympus BX40 polarizing microscope. Two hundred and twenty-nine oriented rock samples were collected; 87 of these samples were cut to make thin sections. Fifty-one additional thin sections from the study area were provided by Dr. Peter Nabelek and Dr. Robert Bauer.

Previous Geologic Mapping

The earliest recorded geologic investigation was conducted and led by General W. F. Harney in 1855 at the bequest of the United States Army (Froiland, 1990). In 1859, Captain W.F. Raynolds and Dr. F. V. Hayden led another expedition into the Black Hills and published the first geological report of the Black Hills in 1869. General George A. Custer led an expedition into the Black Hills in 1874, with Professor N.H. Winchell as geologist, which discovered the presence of gold in the Black Hills. As a direct result of the discovery of gold, the Bureau of Indian Affairs ordered a survey of the Black Hills in 1875, which was directed by Henry Newton and Walter P. Jenny, with fifteen assistants and an escort of 400 soldiers. The results of the survey were published in 1880.

One of the earliest studies conducted in the crystalline rocks of the Black Hills was conducted by Van Hise (1890) who noted the vertical N-S trending slaty cleavage and folds in the vicinity of the Harney Peak Granite. Darton and Paige (1925) first mapped this area as part of the Central Black Hills Folio. Hess (1925) and Landes (1928) published the first reports on pegmatites in the study area. Connolly and O'Harra (1929) first described the geology of ore deposits. Balk (1931) studied the metamorphic enclaves and foliations of the Harney Peak

Granite. During World War II and after, the Black Hills were a locus of numerous investigations by the United States Geologic Survey (e.g., Fisher, 1942, 1945; Gwynne, 1944; Noble and Harder, 1948; Noble et al., 1949; Sheridan et al., 1957; Norton et al., 1962). Previous mapping of the study area was conducted by Norton (1976). Mapping adjacent to and within close proximity of the study area was conducted by Redden (1963, 1968), Ratte and Wayland (1969), Bayley (1970, 1972a, 1972b), Woodland (1979). Dewitt et al. (1986) published a 1:250,000-scale map of the Black Hills.

STRUCTURAL RELATIONSHIPS AND DEFORMATIONAL HISTORY

The Black Hills have undergone multiple episodes of both prograde metamorphism and deformation. The rocks in the study area are primarily of mid- to upper greenschist metamorphic facies except where they have been affected by the metamorphic aureole of the Harney Peak Granite (Figure 6). In the southwestern portion of the study area, rocks immediately adjacent to the Harney Peak Granite contain flattened aggregates of sillimanite with the highest zone recording coexisting sillimanite + garnet + biotite (cf. Helms and Labotka, 1991).   The highest grade metamorphic rocks in the Black Hills occur southwest of the study area, where the second sillimanite isograd occurs adjacent to the Harney Peak Granite (Figure 6; Duke et al., 1988). The timing of Proterozoic deformational and metamorphic events is constrained between 1850 Ma and 1555 Ma (Terry and Friberg, 1990; Redden and Dewitt, 1996). Chamberlain et

al. (2002) proposed two periods of east-west collision: (1) the ~1778 Ma Black

Hills Orogeny resulting from the collision of the Dakota block with the Wyoming

province and (2) the ~1720 Ma Dakotan Orogeny as the terminal collision of the

Wyoming and Superior provinces. Major episodes of folding and faulting

culminated with the intrusion of the Harney Peak Granite at 1715 Ma (^{207}Pb-^{206}Pb

age, Redden et al., 1990), although at least one penetrative fabric within the

study area apparently post-dates the Harney Peak Granite (this study).

Summary of Previous Structural Studies

The earliest deformational fabric in the Black Hills occurs in the Archean

Little Elk terrane and is restricted to the Archean rocks of the terrane (Gosselin,

et al., 1988). The Little Elk terrane has two distinct fabrics: an older east-

northeast-trending foliation found in the surrounding (Archean) biotite-feldspar

gneisses and a younger, strong northwest-trending foliation in the granite proper

that cross-cuts the earlier northeast-trending fabric (Gosselin et al., 1990).

Gosselin et al. (1990) interpreted the younger foliation to be contemporaneous

with the emplacement of the Little Elk Granite and suggested, based on the 1850

Ma Rb-Sr whole rock age of Zartman and Stern (1967), and the similar

orientation of the dominant fabric in Proterozoic rocks elsewhere in the Black

Hills, that this foliation was reactivated during Paleoproterozoic deformational

events. The Bear Mountain terrane also records an earlier, weak east-northeast

trending bedding-plane foliation in the encapsulating younger sequence of

Paleoproterozoic metasedimentary rocks and a younger concentric foliation that outlines the structural dome seen both in the Archean schists and, to a lesser degree, in the Bear Mountain Granite *sensu stricto* (Gosselin et al., 1990; Redden et al., 1990). This younger foliation is interpreted to have formed contemporaneously with doming that is postulated to be a result of the emplacement of an underlying unexposed pluton of the Harney Peak Granite based on 1680±25 Rb-Sr muscovite ages from the flank of the Bear Mountain dome (Zartman, *in* Ratte, 1986; Redden et al., 1990). Dahl et al. (2005a,b a,b) reported an early ENE-trending fabric preserved in the cores of garnet porphyroblasts from the Bear Mountain dome. The east-northeast foliation observed in the younger Paleoproterozoic sequence overlapping the Bear Mountain terrane has been related to early Central Plains orogeny ca. 1775 Ma (Dahl et al., 2005 a,b).

The most complete summary of deformational events affecting the Proterozoic rocks of the Black Hills is given in Redden et al. (1990). The earliest event, D_1, has been inferred from the cryptic presence of east-northeast-trending, north-vergent, F_1 fold nappes recognized on the basis of top and bottom criteria (Dewitt et al., 1989; Redden et al., 1990). No penetrative fabric or metamorphism are associated with the D_1 event in the Black Hills, although the early ENE-trending fabric reported by Dahl et al. (2005 a,b) may indicate that this event was locally penetrative in nature. The timing of this event is unclear, but it may represent the earliest arrival of a southward-younging (1790-1630 Ma)

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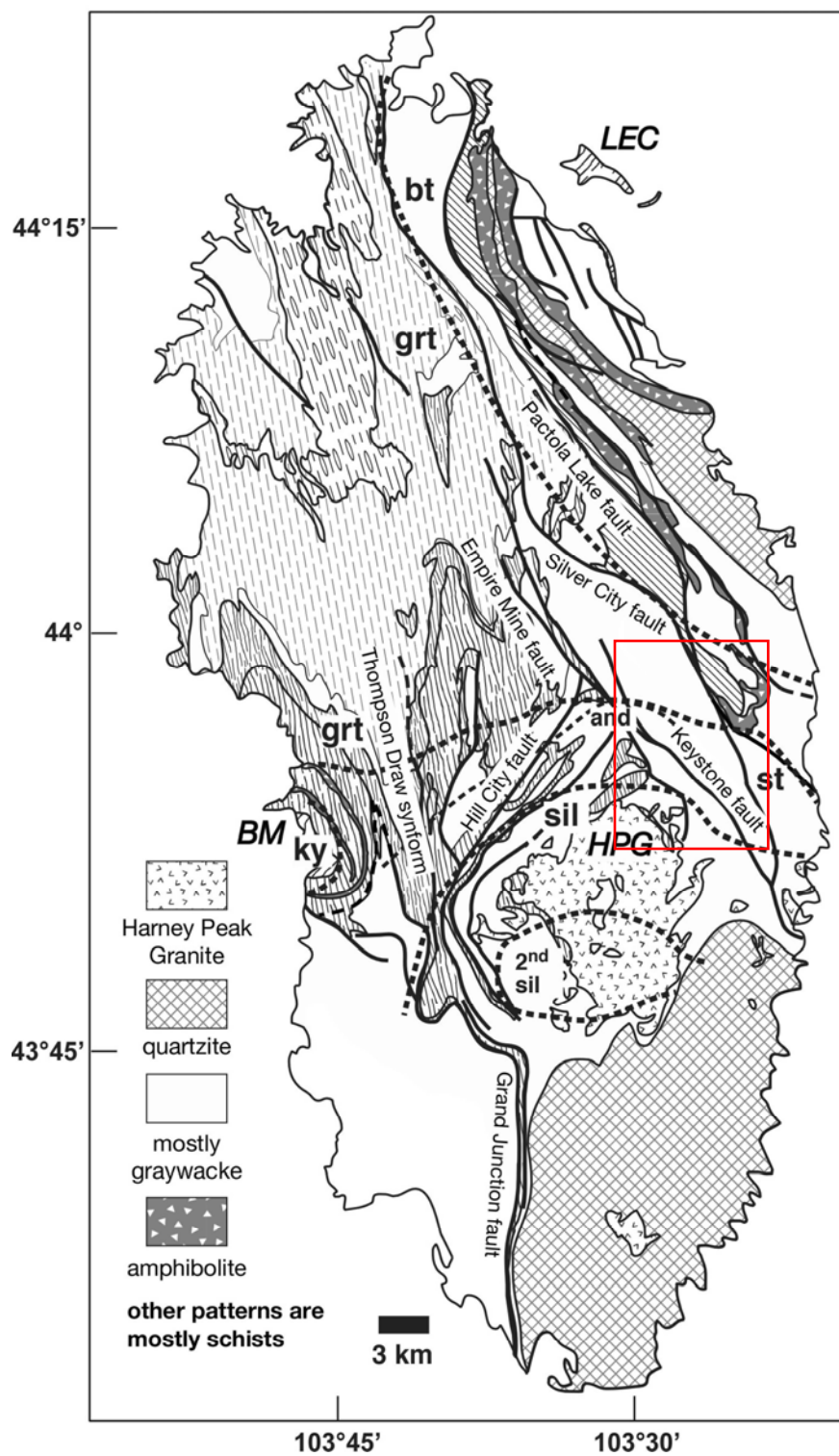
Figure 6 - Metamorphic zones of the Precambrian Black Hills (from Nabelek et al., *in press*). Red box is approximate location of study area. BM = Bear Mtn granite; HPG = Harney Peak granite; LEC = Little Elk Granite.

32
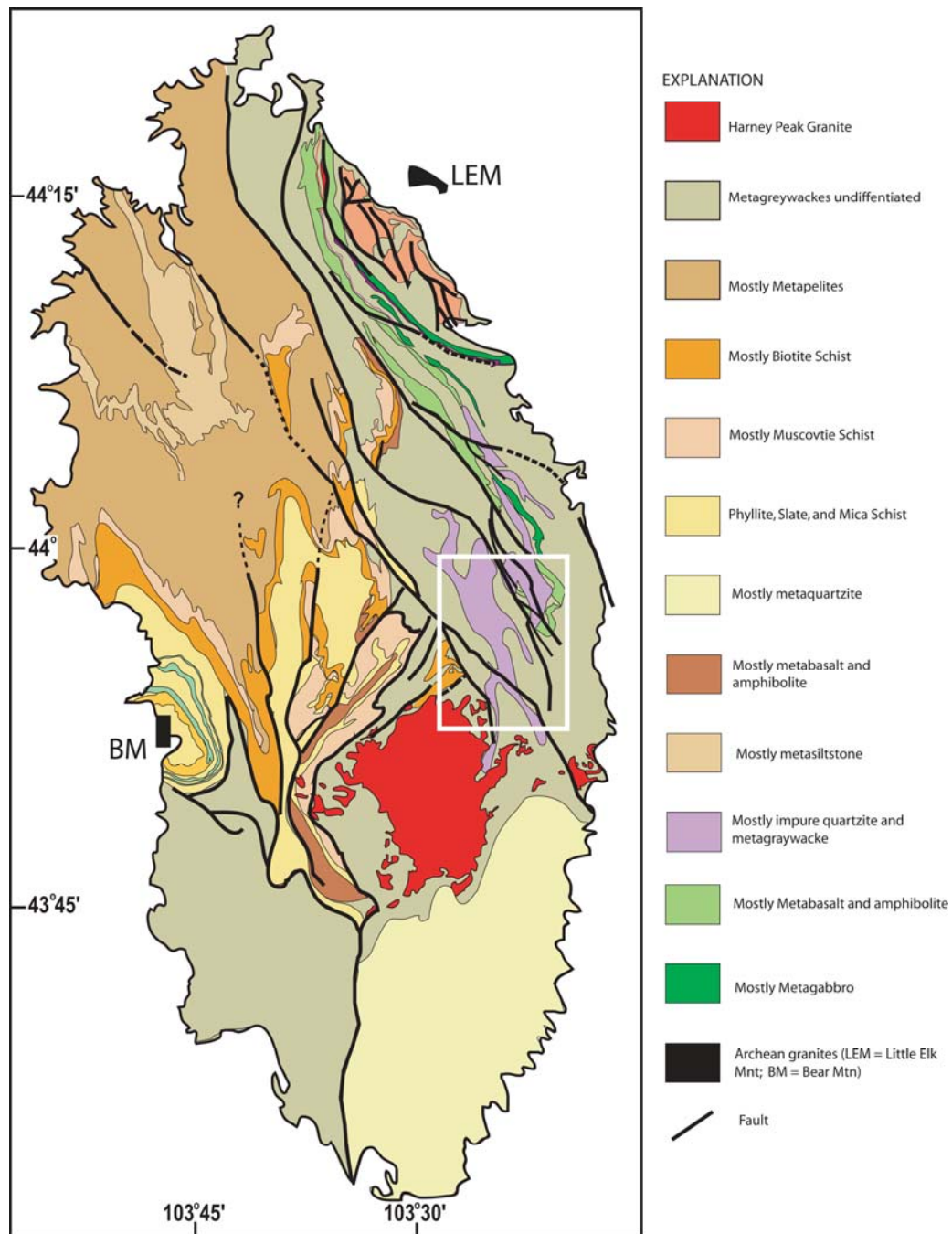
Figure 7 - Generalized geologic map of the Precambrian Black Hills showing location of the Archean terranes and major structural features. Note the overall pattern of faulting and resultant displacement of mappable units northeast of the Harney Peak Granite. Mapped adapted from Dewitt et al. (1986), Ratte and Wayland (1969), Ratte (1986), and unpublished maps of the Silver City quadrangle. White box represents approximate location of the study area.

collage of island-arcs that make up the Central Plains orogeny (Dewitt et al., 1989; Redden et al., 1990; Dahl et al., 1999a; Sims and Peterman, 1986; Bickford et al., 1986; Sims et al., 1991). Dahl et al. (2005 a,b) suggest a 1775 ± 10 Ma age for this event.

The dominant structural fabric in the Black Hills is associated with the D_2 deformational event and associated regional metamorphism (M_1). The D_2 event produced north- to northwest-trending upright folds (F_2) that refolded F_1 folds (Redden et al., 1990). The D_2 event is generally considered to be associated with east-west collision of the Wyoming and Superior provinces. D_2 produced a locally penetrative, steeply dipping axial-planar foliation (Dewitt et al., 1989). This axial-planar foliation has been designated S_2 because an earlier fabric (S_1) is preserved as oblique inclusion trails in regionally metamorphosed garnets (Dahl et al., 1999a). However, it is not clear whether S_1 is associated with D_1, represents the early stages of D_2, or represents garnet overgrowth of a primary compositional banding/bedding unrelated to deformation (i.e. is actually S_0).

The cryptic D_3 event resulted in F_3 "cross-folds." D_3 is of uncertain age and origin, but purportedly refolds F_1 and F_2 folds in the northern and central Black Hills, most notably in the Pactola Reservoir area just north of the study area and near the Dearfield area east of Silver City (Redden et al., 1990). The relationship between D_3 and other fabrics remains uncertain. F_3 folds have been interpreted to be a late-stage modification of F_2 folds by a major shear couple affecting the Black Hills during the waning stages of continental assembly (Redden et al., 1990; Dahl et al., 1999a). Localized doming of country rocks (D_4)

and metamorphism (M_2) accompanied emplacement of the Harney Peak Granite and hundreds of associated granitic dikes and pegmatites (Norton and Redden, 1990). D_4 produced local folds and schistosity associated with doming, locally transposing the dominant S_2 fabric into S_4. A post intrusion D_5 event, which produced a northeast-trending fabric across the central Black Hills ca. 1535 Ma, has been suggested by Redden et al. (1990), presumably as a far-field response to the Central Plains orogen. Table 2 is a summary of deformation and related structures as outlined above.

Despite the structural framework discussed above and outlined in Table 2, many questions regarding the structural history of the Proterozoic Black Hills remain unresolved. Previous workers have assumed that all the Paleoproterozoic rocks of the Black Hills have experienced the same sedimentologic, tectonic, and structural histories and have constructed a complicated tectonic model to explain this assumption (e.g., Redden et al., 1990; Terry and Friberg, 1990; Helms and Labotka, 1991; Dahl et al., 1999 a,b, 2005 a, b). For example, the oldest Paleoproterozoic rocks are restricted to a few fault-bounded blocks in the Nemo area and do not outcrop elsewhere in the Black Hills. Should not a vestige of this sequence be seen in the temporally equivalent Bear Mountain terrane? The lithologic differences between parts of the Black Hills separated by faults has been attributed to multiple ensialic rift basins (Redden et al., 1990) which leads to an abstruse explanation of Black Hills

	Folds		Fabrics
	Style	**Orientation**	
D_1	Tight to Isoclinal	Northeast-trending, overturned to north-northwest	S_1 – relict foliation in garnet representing early stages of D_2 (Dahl et al., 1998a)
D_2	Isoclinal	North to northwest trending, upright	S_2 – steeply dipping axial planar foliation *S_1 of Redden et al., (1990)
D_3	Upright, tight – isoclinal, doubly plunging (Redden, pers. comm., 2001); deforms F_2	More westerly than F2 folds to east-west, moderate to steep plunges	S_3 – generally non-penetrative foliation (?)
D_4	Doming and associated local folds; refolds earlier folds	Variably oriented	S_4 – schistosity associated with granite emplacement
D_5	Small, late folds locally recognized	Northeast trending	S_5 – northeast trending axial-planar foliation to spaced cleavage *S_4 of Redden et al., (1990)

Table 2 - Summary of Proterozoic deformational events and related structures. See text for explanation. Data summarized from Redden et al., (1990), Dahl et al., (1998), Dewitt et al., (1989), and Noble et al., (1949).

tectonism. This follows from the assumption that all the rocks have the same

histories, which is likely not the case. Moreover, a multitude of deformational

events have been ascribed to the Black Hills but not all parts of the Black Hills

record all episodes of deformation. The following section discusses the

relationship between multiple deformational fabrics within the Mount Rushmore quadrangle and their relationship to previous studies.

Deformational Events and Features Considered in this Study

The study area has been divided up into nine fault-bounded blocks (Figure 5). These fault-blocks have different structural histories and are used as structural domains in this study. The attitude of structural features is first discussed with respect to the major deformational events (Table 2) for the study area as a whole. The variations among the structural domains are then discussed to help elucidate the structural history of the study area.

Three distinct deformational events have been recognized in the study area. These events correspond to the D_2, D_4, and D_5 regional events as outlined in Table 2. I have chosen to refer to these events within the regional context of deformational events reported for the Black Hills (e.g. D_2-S_2-F_2, etc.) despite the fact that within the study area and fault-blocks they represent local D_1, D_2, and D_3 events and related structures. Unnecessary complication will be avoided by referring to these events with respect to the overall regional context as reported in the literature and will allow the reader to evaluate this study more easily in the regional context. However, it must be recognized that in doing so, this author is not implying that the deformational history as outlined in Table 2 is strictly applicable to the study area. Moreover, not all fault blocks record all deformational events.

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Bedding, Primary Sedimentary Structures, and Compositional Variation

Much of the Mount Rushmore quadrangle is underlain by moderately metamorphosed sedimentary sequences, which in many instances preserve primary sedimentary structures. Bedding (S_0) is the most prevalent primary structure recognized, but is not ubiquitous, nor consistent, throughout the study area. Where it is recognized unequivocally, bedding consists mainly of thinly laminated compositional variations in finer grained metasedimentary rocks whereas thicker beds preserve primary sedimentary structures such as cross bedding, particularly in coarser metagraywackes. Graded bedding characteristic of turbidites is common. Disrupted bedding and soft-sediment deformation are also recognized.

Most metasedimentary rocks show some compositional banding that has been interpreted as bedding by previous workers, but is not likely to be primary layering formed during deposition (Figure 8). As such, it cannot be bedding *sensu stricto* and is referred to herein as compositional banding (S_c). In many cases, true bedding and compositional banding may be present simultaneously. Where this occurs, bedding (S_0) is usually sub-parallel to the compositional banding (Figure 9). In other instances, compositional banding may look essentially like bedding at the meso-scale and can only be correctly identified microscopically (Figure 10). The origin of the compositional banding may be a compaction

Figure 8 - (A) Typical lichen covered exposure of metasedimentary rocks within the study area. Note the prominent layering of the rocks and the younger spaced cleavage trending from lower right to upper left in the left exposure. Most previous workers have generally designated layering such as this as bedding (S_0). But is it? The difficulty is not recognizing the layering but determining the origin of the layering. See Figure 9 for comparison. **(B)** Overlay showing younger spaced cleavage direction (red lines). Hammer for scale is 32.5 cm long.
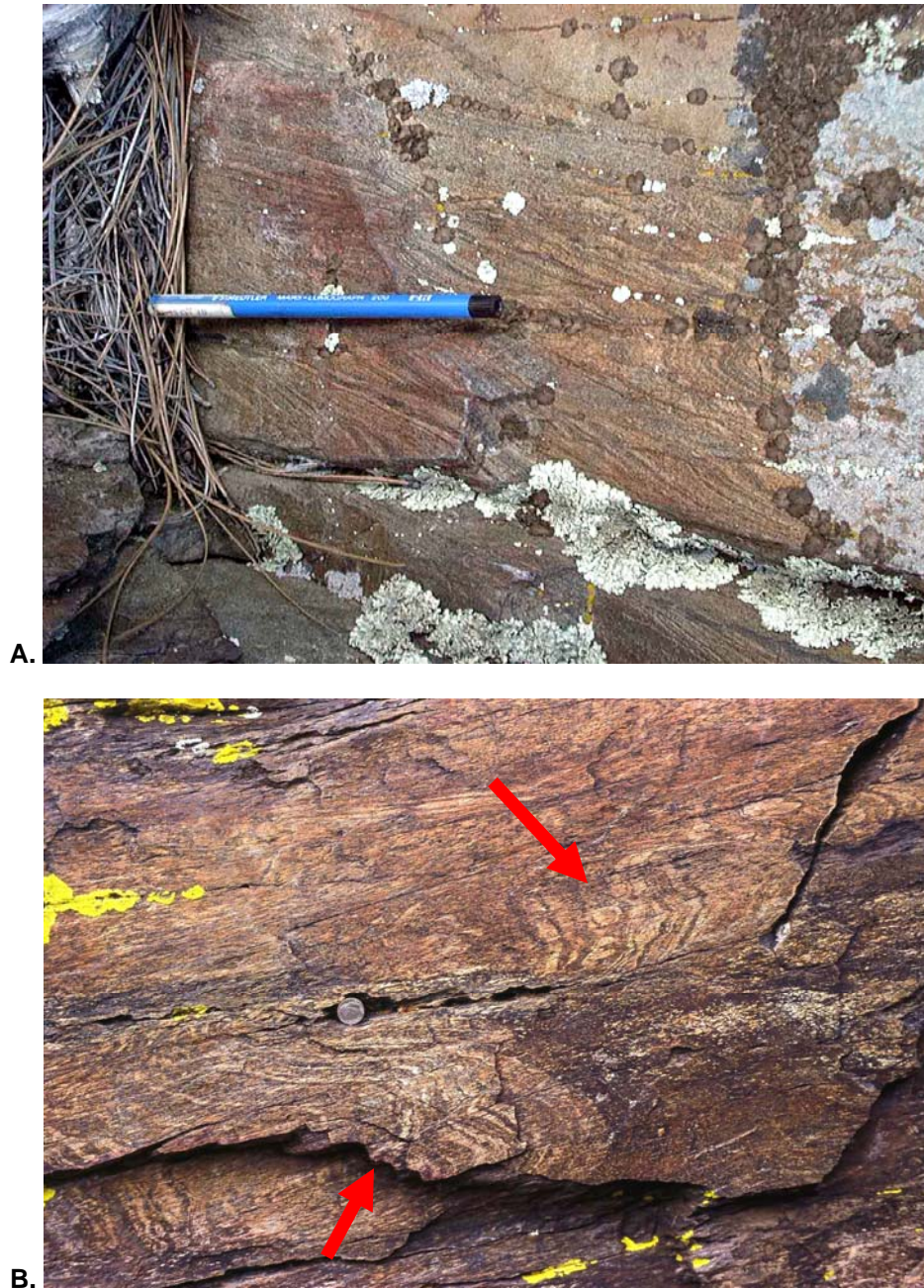
Figure 9 - Atypical exposures of the typical relationship of bedding (S_0) to compositional banding (S_c) in metapsammites within the study area. **(A)** S_c trends gently downward from left to right. Note the abrupt change in dominant lithology and grain-size in the upper part of the photograph delineating S_c. Bedding (S_0) is subparallel to S_c and is expressed as mm-scale banding in the center of the photograph. The blue pencil is parallel to small shear bands. Fortunately, this small section of the outcrop was not completely covered in lichen permitting the recognition of S_0. Pencil is 14 cm long. **(B)** Sheared S_0 (red arrows) is cut by dominant S_2 fabric, which trends at a shallow angle from lower left to upper right. Note US dime for scale.
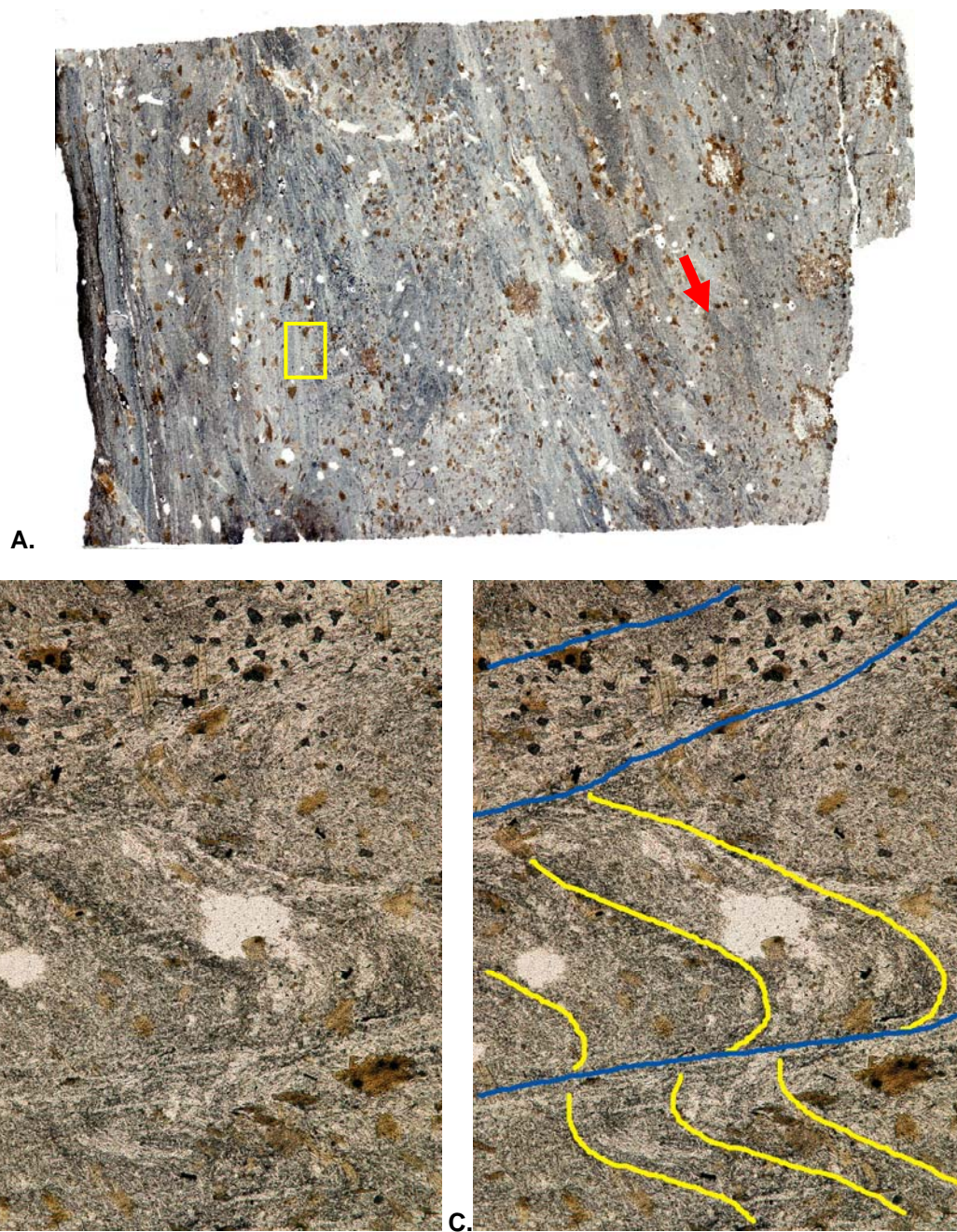
Figure 10 - Example of bedding recognition through petrographic analysis. **(A)** Plane polarized light scan of representative thin section MR266, a quartz-mica schist. Note the overall layered appearance of the section and the younger spaced cleavage trending subvertically (red arrow) bottom-right to upper-left that is especially prominent in the center right of the photomicrograph. Compositional banding (S_c) may be easily mistaken for true bedding in the field. Yellow box located left center is approximate field of view for (B) and (C). Thin section is standard size 27 mm X 46 mm. **(B)** Magnified view of area delineated by yellow box in part (A). Note true bedding in center of photomicrograph trending top left to bottom right between zones of dominant foliation (S_c). Bedding is apparently sheared along bottom contact. Field of view is approximately 0.3 by 0.5 mm. **(C)** Same as (B) with overlay showing bedding S_0 (yellow lines) and dominant foliation S_c (blue lines) for clarity.

foliation, tectonic in origin or perhaps an effect of metamorphic segregation.

Regardless, great care was taken during this study when assigning the term

"bedding" because of the structural and tectonic implications implied by its usage.

The use of the term bedding was restricted to areas where I was convinced that

the structure was primary, for example recognition of graded bedding or cross-

beds. In all other instances, I refer to the foliation as compositional banding (cf.

Figures 8 – 10).

D_1 Deformation

Regional D_1 deformation is attributed to a series of north-directed nappes

emplaced as thin-skinned foreland thrust complexes that overrode the

southeastern Wyoming craton (Dewitt et al., 1989; Redden et al., 1990; Dahl et

al., 1999a, 2005a,b). The Cheyenne fold belt has been interpreted as the root of

these nappes (Condie and Shadel, 1984; Duebendorfer and Houston, 1987;

Premo and Van Schmus, 1989; Houston et al., 1989; Dahl et al., 1999a). The

Black Hills would represent the northern extent of nappe emplacement during the

onset of the 1780-1740 Ma Medicine Bow orogeny (Chamberlain, 1998).

However, Redden et al. (1990) constrained the age of D_1 deformation to 1884-

1840 Ma, and Dahl et al. (1999a, 2005a,b) suggested a circa 1790-1780 Ma age

for onset of D_1 based on biotite cooling ages and U-Th-Pb monazite ages.

Chamberlain et al. (2002) proposed a ~1778 Ma date for this early event in the

Laramie Range based on U-Pb ages of syn-deformational sphene. Recent work

in the Black Hills by Dahl et al. (2005a,b) has constrained the D_1 event between 1785 and 1775 Ma. The attribution of the D1 event remains uncertain.

Foliation

Previous workers have reported that no fabric is associated with D_1 (e.g., Redden et al., 1990), however Dahl et al. (2005 a,b) report a presumed S_1 relict fabric in garnet porphyroblasts from a single sample taken from the younger Paleoproterozoic sequence outcropping ~1 km east of Bear Mountain. Evidence for an S_1 foliation was not observed in the study area, with the possible exception of fault-block B. Rocks in fault-block B typically have two fabrics, original bedding and a weak foliation that is axial planar to recumbent tight to isoclinal folds that have shallow axial planar dips (Figure 11). This axial planar fabric may be related to D_1, although that interpretation is equivocal. Two possibilities exist for the paucity of early S_1 fabrics: (1) the penetrative nature of later deformational events throughout the majority of the study area transposed S_1, or (2) the fault-bounded blocks along the east side of the Black Hills do not record this earlier event. The absence of pre-Harney Peak porphyroblasts in the study area as compared to areas west of the Keystone fault supports the latter possibility but does not preclude the former. It is also possible that the absence of pre-Harney Peak porphyroblasts could be because the rocks never reached sufficient temperatures to produce M_1 related porphyroblasts. The origin of the compositional banding (S_c) described above may also be related to D_1 deformation.

Dahl et al. (1999a) reported inclusion trails in garnets that are oblique to the S_2 foliation and may be relict fabrics associated with D_1. Dahl et al. (2005a,b) reported relict east-northeast-trending foliations in garnet porphyroblasts in two samples of metapelite from the Bear Mountain dome. However, it is unclear how the recognition of an S_1 fabric in a single sample by Dahl et al. (2005a,b) in kyanite grade rocks at the Bear Mountain locality (i.e., presumably deeper crust) may be evaluated with respect to the lack of penetrative S_1 fabrics reported by earlier workers (e.g. Redden et al., 1990). Dahl et al. (1999a; 2005a,b) presented no argument to preclude their reported S_1 from being preserved bedding. Weak axial planar foliations of early formed recumbent isoclinal folds observed west of the study area in the Hill City quadrangle, similar to that observed in fault-block B, may also be S_1. However, as discussed below, it is likely that fault-block B has a distinct structural history and that the weak axial planar fabric is related to the D_2 event.

Folds

Unequivocal evidence for the F_1 folding was not recognized in the Mt. Rushmore quadrangle. Two examples of large-scale F_1 folding that occur in the study area were shown to this author by Dr. Jack Redden of the South Dakota School of Mines and Technology (retired). Both examples are described briefly in Redden and Duke (1996), stops one and two, in the road log of field trip nine of the field guide. In both instances, I remain unconvinced of the interpretation of the outcrops. The first example, located in the extreme northeastern portion of

the Mt. Rushmore quadrangle, is based on the recognition of a northeast-trending "antiformal syncline" as determined by graded-bedding on opposite limbs of the fold. After multiple, careful examinations of the outcrop, I have not been able to convince myself of the unequivocal existence of the fold, nor did I find any evidence for such folds in the immediate environs. The second example is located along the central eastern-edge of the Mt. Rushmore quadrangle. In this case, the main argument for the existence of early F_1 folds is based on lineations that wrap across perceived fold hinge-lines (Redden, 2001 pers. comm.). Even if the early folds exist, wrapping of early-formed lineations across the hinge-lines of the folds can be easily explained by progressive noncoaxial strain during folding (Hobbs et al., 1976, pg. 192).

Although little evidence for large-scale F_1 folds exists in the Mt. Rushmore quadrangle, bedding (S_0) has been locally reoriented by F_1/F_2(?) folds. However, as discussed below, these folds may be F_2 folds that have been locally reoriented by the emplacement of the Harney Peak Granite. Occurrence of F_1/F_2(?) folds in the study area is ostensibly restricted to fault-blocks A and B (Figure 5), but F_1 folds have been reported by other workers in the Mount Rushmore quadrangle and throughout the Black Hills (Redden and Duke, 1996; Redden, 2001 pers. comm.). Where recognized by other workers, F_1 folds have generally northeast-trending orientations and are moderately to steeply plunging. Recognition of early F_1 folds in the Mount Rushmore quadrangle is difficult because of transposition of S_0 by later fabrics. However, within fault-blocks A and B (Figure 5) north of the Harney Peak Granite, these early F_1/F_2(?)

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A.

B.

Figure 11 - (A) Photograph of early recumbent fold of interbedded metagraywacke and micaceous schist east of Hill City on Highway 16/385, just west of the study area in the Hill City quadrangle, looking N. A weak axial planar cleavage (S_1), roughly parallel to the road, is evident in this early F_1-fold. Multiple folds like this exist in fault-block A of the study area, but are not as well exposed. Note the 1987 Chevy Blazer for scale. **(B)** Weak axial-planar fabric of the early F_2 folds shown in hand-sample. "Spots" trending across the layer from lower left to upper right define the foliation and are typically biotite clots that surround quartz centers. Layering is likely S_0 and the spots define local S_1. Layer is approximately 8 cm thick.

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structures are generally tight to isoclinal, recumbent folds with gently dipping

axial surfaces that either lack or have a very weak axial planar fabric. These

folds are similar to folds in the Hill City quadrangle, west of the Mount Rushmore

quadrangle, that may be related to D_1 (Figure 11).

D_2 Deformation

The dominant structural features and M_1 regional metamorphism in the

study area are associated with the D_2 event. D_2 is attributed to the east-west

collision of the Wyoming and Superior provinces and has been widely interpreted

to be the southern extension of the Trans-Hudson orogen (Green et al., 1979,

1985; Sims and Peterman, 1986; Van Schmus et al., 1987; Klasner and King,

1990; Houston, 1993; Baird et al., 1996), although strict usage of the term Trans-

Hudson is problematic. For instance, Nabelek et al. (2001) and Chamberlain et

al. (2002) suggested that the D_2 event was a result of east-west collision

between the Wyoming province and the Dakota block, an intervening crustal

block of uncertain origin recognized from geophysical data (e.g. Baird et al.,

1996). Redden et al. (1990) constrained the timing of the D_2 event between

1880 Ma and 1715 Ma, prior to the intrusion of the Harney Peak Granite (1715

Ma) and after the deposition of the supracrustal sequences (ca. 1880 Ma; Dahl et

al., 1999a). Redden et al. (1990) assigned an 1840±70 Ma age for D_2

deformation based on Rb-Sr whole rock "disturbed isochron" data from the

Archean Little Elk Granite reported by Zartman and Stern (1967). However,

reset whole-rock Rb/Sr data are highly suspect because of limits to Sr

rehomogenation (eg. Lanphere et al., 1964; Herman et al., 1986; Faure, 1986).

Recalculation of these data by Dahl et al. (1999a) yielded an 1800±70 Ma

estimate, offering little improvement. Recent Pb-Pb dates of garnets and

$^{40}Ar/^{39}Ar$ data from metamorphic rocks suggest 1770-1740 Ma age for the

regional D_2 event (Dahl et al., 1999a, 1999b, 2000). Recent work by Dahl et al.

(2005a,b), suggested a circa 1775 Ma date for the D_2 event.

Foliation

The dominant planar feature within the study area is the S_2 foliation. The

S_2 foliation is also the most pervasive fabric element in the metamorphic rocks of

the Black Hills. S_2 is a locally penetrative, north- to northwest-striking, steeply

dipping foliation that is axial-planar to steeply plunging isoclinal F_2 folds. This

axial-planar foliation has been designated S_2 because an earlier fabric

(presumed S_1) is preserved as oblique inclusion trails in regionally

metamorphosed garnets (Dahl et al., 1999a; 2005a,b). However, as noted

above, it is not clear whether this reported S_1 fabric is associated with D_1,

represents the early stages of D_2, or is preserved bedding (S_0).

S_2 is most easily distinguished in the noses of F_2 folds (Figures 12 and

13). S_2 is a composite foliation in the limbs of the F_2 folds, where it typically

parallels earlier compositional banding or bedding. S_2 typically ranges from a

continuous, slaty cleavage in more micaceous units to a spaced, crenulation

cleavage in more quartz-rich units. S_2 may also be recognized as an

anastomosing slaty cleavage in some instances. Microscopically, S_2 may be
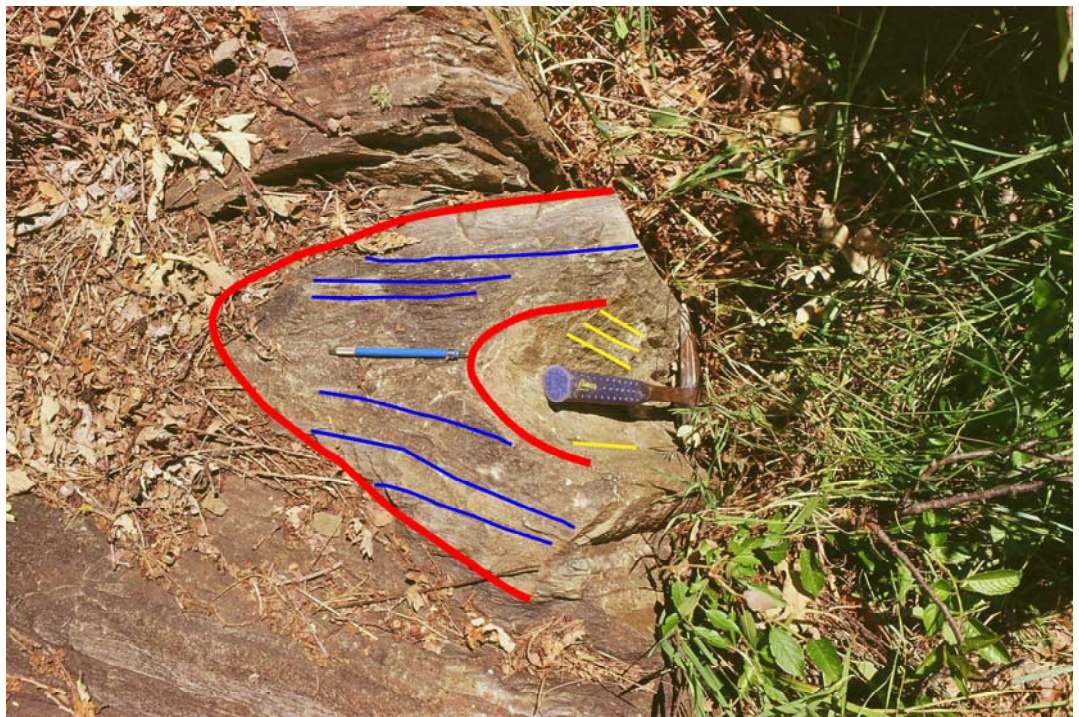
Figure 12 - (A) Photographs of F_2 fold in mica-quartz schists showing S_2 axial planar cleavage. Pencil is parallel to S_2 and hammer is parallel to the plunge of the F_2 fold. L_2 intersection lineations (see text below) is evident above the hammer handle. **(B)** Overlay showing F_2 fold (red), S_2 foliation (blue), and L_2 lineation (yellow). Hammer handle is parallel to the S_2 foliation intersection with folded S_0. Pencil is 14 cm long. Hammer is 32.5 cm long. Fault-block H.
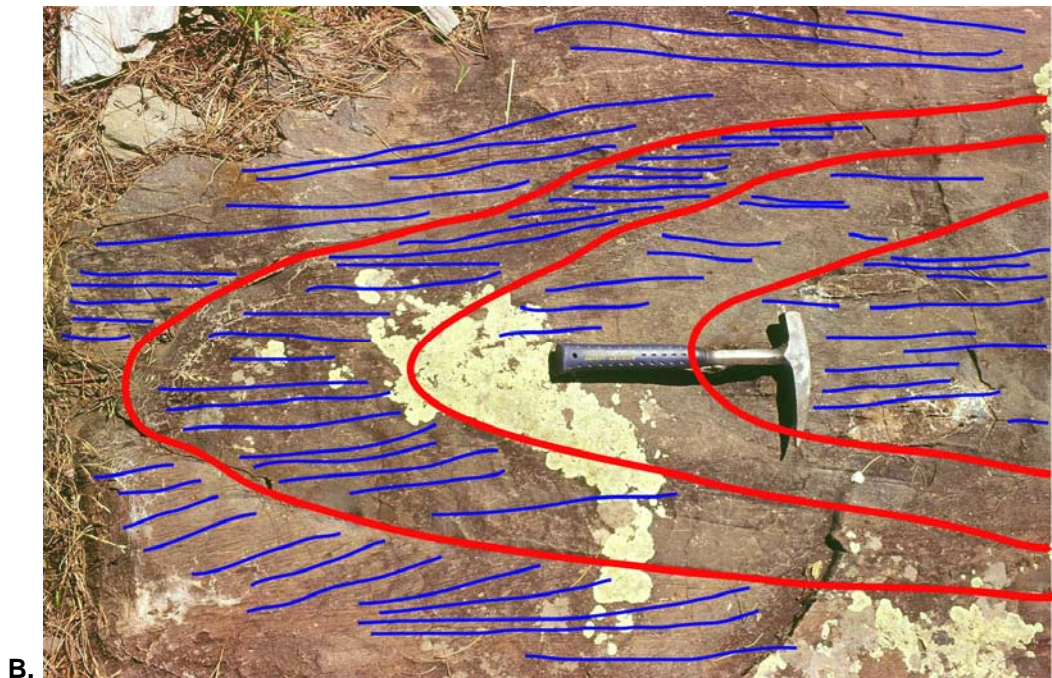
Figure 13 - (A) Outcrop photographs of F_2 fold showing S_2 axial planar cleavage in folded mica-quartz schists. F_2 fold has nearly vertical plunge and steeply dipping axial surface. Hammer handle is parallel to the S_2 foliation direction. Note calc-silicate boudins marking the limbs of a folded layer just to the right of hammer head. Pencil is 14 cm long. Hammer is 32.5 cm long. **(B)** Overlay indicating compositional layering outlining the fold (red) and trace of S_2 foliation. Note the thickened hinge zones and attenuated limbs of the F_2 folds and the refraction between different compositional layers. Fault-block H.

Figure 14 - Photomicrographs of S_2 foliation demonstrating its variable nature. **(A)** Spaced S_2 cleavage in fine-grained graphitic metasiltstone. **(B)** Overlay of A showing compositional layering (Sc) in red and S_2 in blue. **(C)** Spaced S_2 defined by preferred grain orientation and elongated quartz stringers in metapsammites. **(D)** Overlay of C showing S_2 in blue. Note the sheared compositional banding (red arrow). Photomicrographs A-D are standard thin-sections (27 x 46 mm).

A.

B.
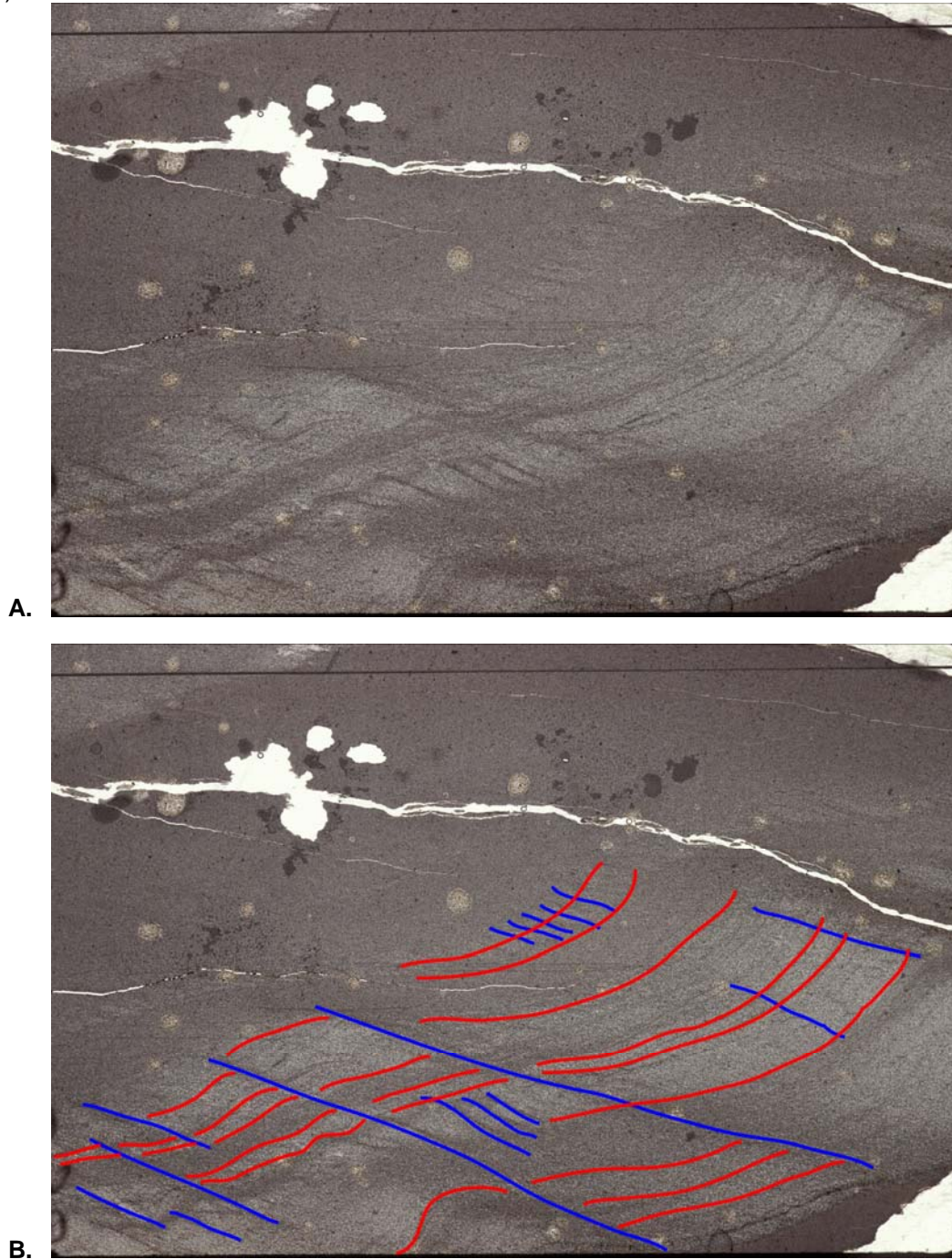
C.
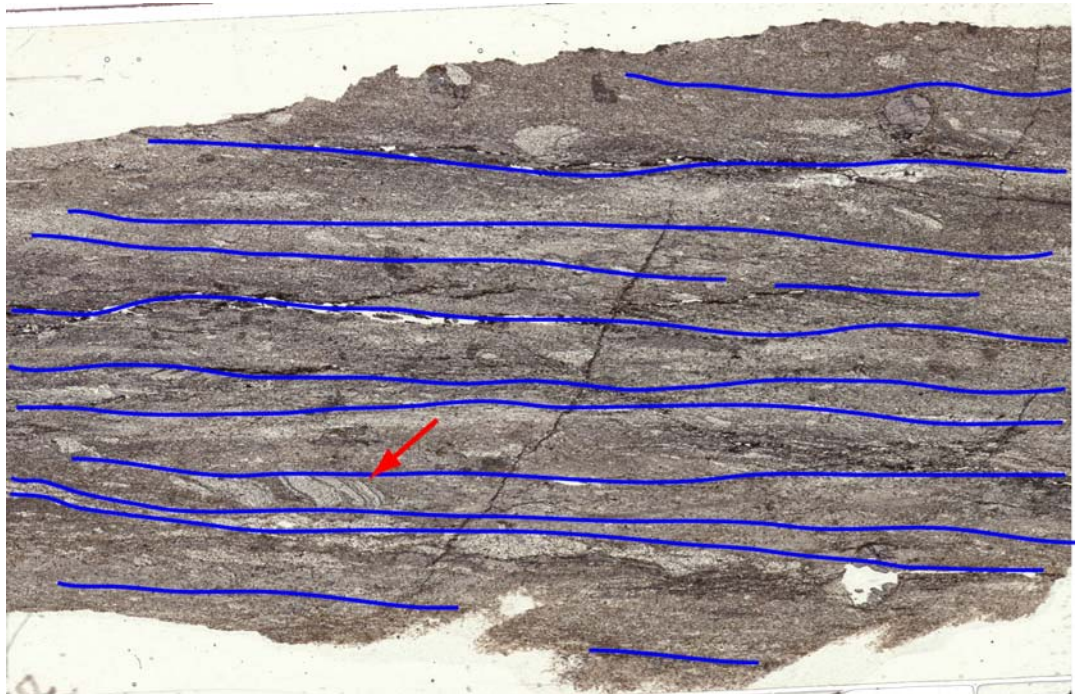
D.

recognized as a preferred orientation of grain boundaries and as the bounding

surfaces of microlithons or shear zones at a high angle to bedding or

compositional banding (Figure 14).

Variations in S_2 and Related Structures Across the Study Area

The orientation of S_2 varies among the fault-blocks (Figure 5). Fault-

blocks A, B, and C show markedly different structural patterns than fault-blocks D

– I (Figures 15, 16, and 17). Fault-block A is strongly overprinted structurally by

the Harney Peak Granite intrusion, and the orientation of the dominant foliation in

fault-block A is directly related to the emplacement of the Harney Peak Granite.

It is not clear how many earlier fabrics existed in fault-block A prior to the Harney

Peak Granite intrusion, but all earlier fabrics have been flattened and reoriented

by the intrusion. Fault-block B is separated from block A by a cryptic structure,

called the Elk Mountain lineament by Ratte and Wayland (1969), in the adjacent

Hill City quadrangle (to the west). I interpret the lineament to be a fault. Rocks in

fault-block B are unaffected by the Harney Peak Granite, likely indicating a

different deformational history for this block. Fault-block B contains no outcrops

of granite and/or pegmatite, and earlier fabrics show no modification by the

intrusion. The southern half of fault-block C shows an overall flattening of pre-

existing, steeply dipping fabrics by the emplacement of the Harney Peak Granite,

while the northern portion of the fault-block is little affected. The southern portion

of fault-block C also contains many of the better known pegmatite mines (e.g.

Etta, Hugo, etc), and the overall flattening of S_2 may be
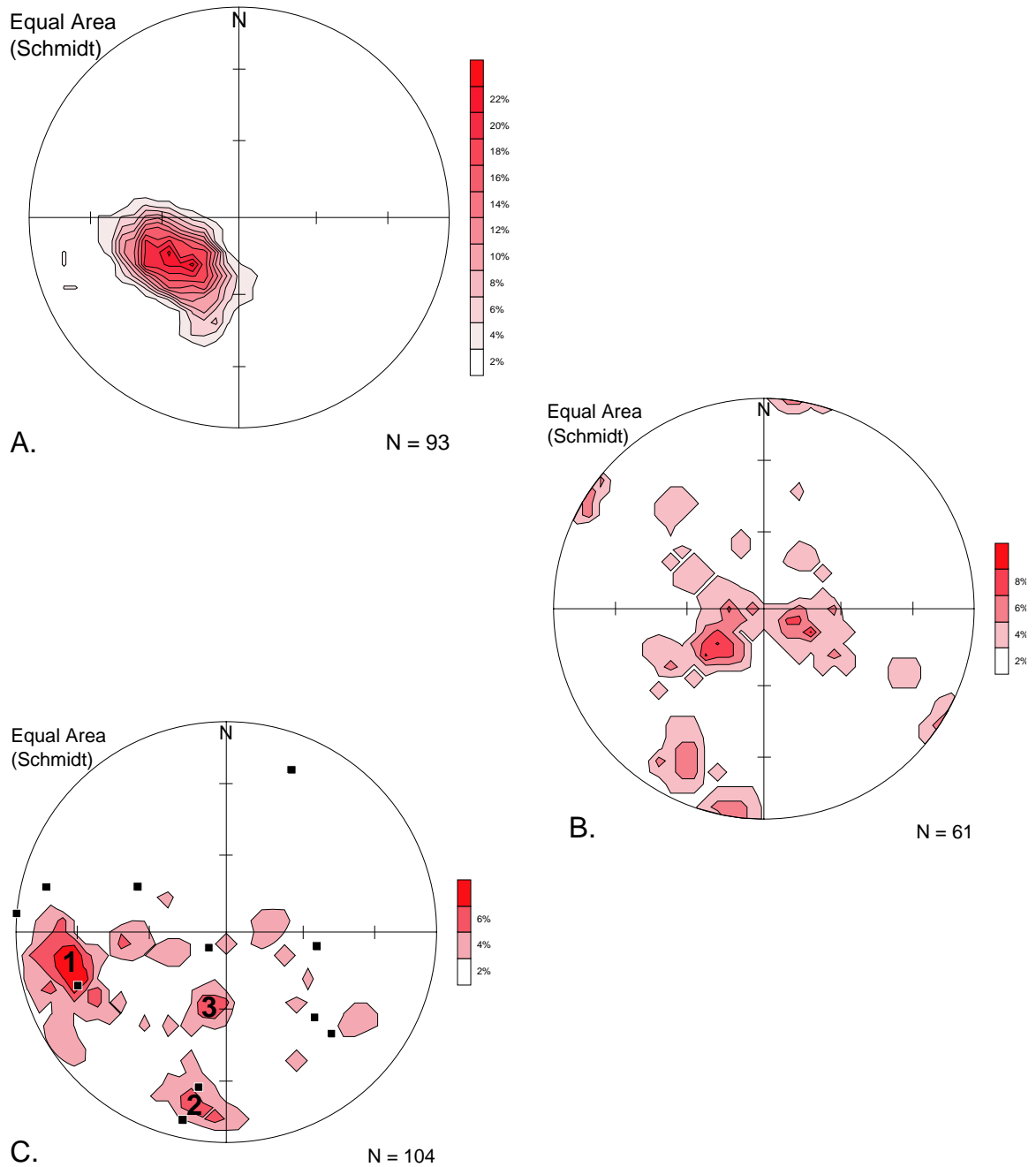
Figure 15 - Lower hemisphere equal area projections (intensity per 1% area) of contoured poles to dominant foliation and axial-planes of F_2 folds (black squares). **(A)** Fault-block A (S_2). **(B)** Fault-block B (S_0/S_c). **(C)** Fault-block C (S_2/S_c). Overlayed numbers 1 and 2 are interpreted to be the limbs of recumbent F_2 folds while 3 is interpreted to be Harney Peak deformation. See text for explanation. Note the overall flattening of S_2 foliation in (A) and overall shallowly dipping fabric in (B). Fabric in B may not correspond to the regional S_2 foliation, although it is the second fabric recognized in fault-block B. This fabric may be S_1, and if so, this indicates a different tectonic history for fault-block B. See text for discussion.

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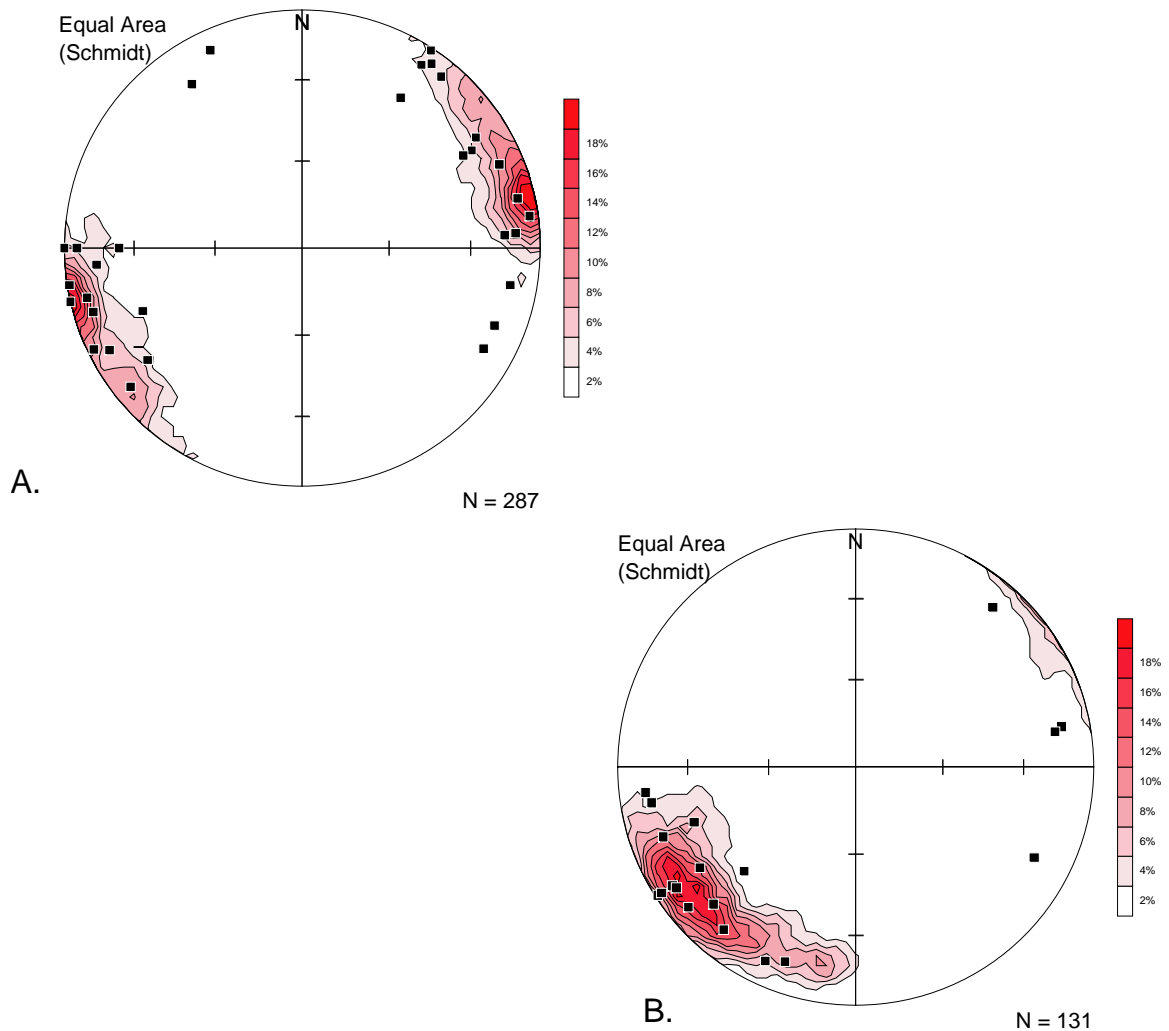
Figure 16 - Lower hemisphere equal area projections (intensity per 1% area) of contoured poles to S_2 foliation and axial-planes of F_2 folds (black squares). **(A)** Fault-blocks D and E. **(B)** Fault-blocks F and G. Note the slight variation in strike direction between fault-blocks but the pattern remains very similar overall. The pattern in (A) is dominated by a map-scale F_2 fold that is evident on the map of the study area (Plate I) in fault-block E. Fault-blocks F and G show a very strong linear fabric. Overall patterns are very dissimilar to fault-blocks A – C (cf. Figure 15).
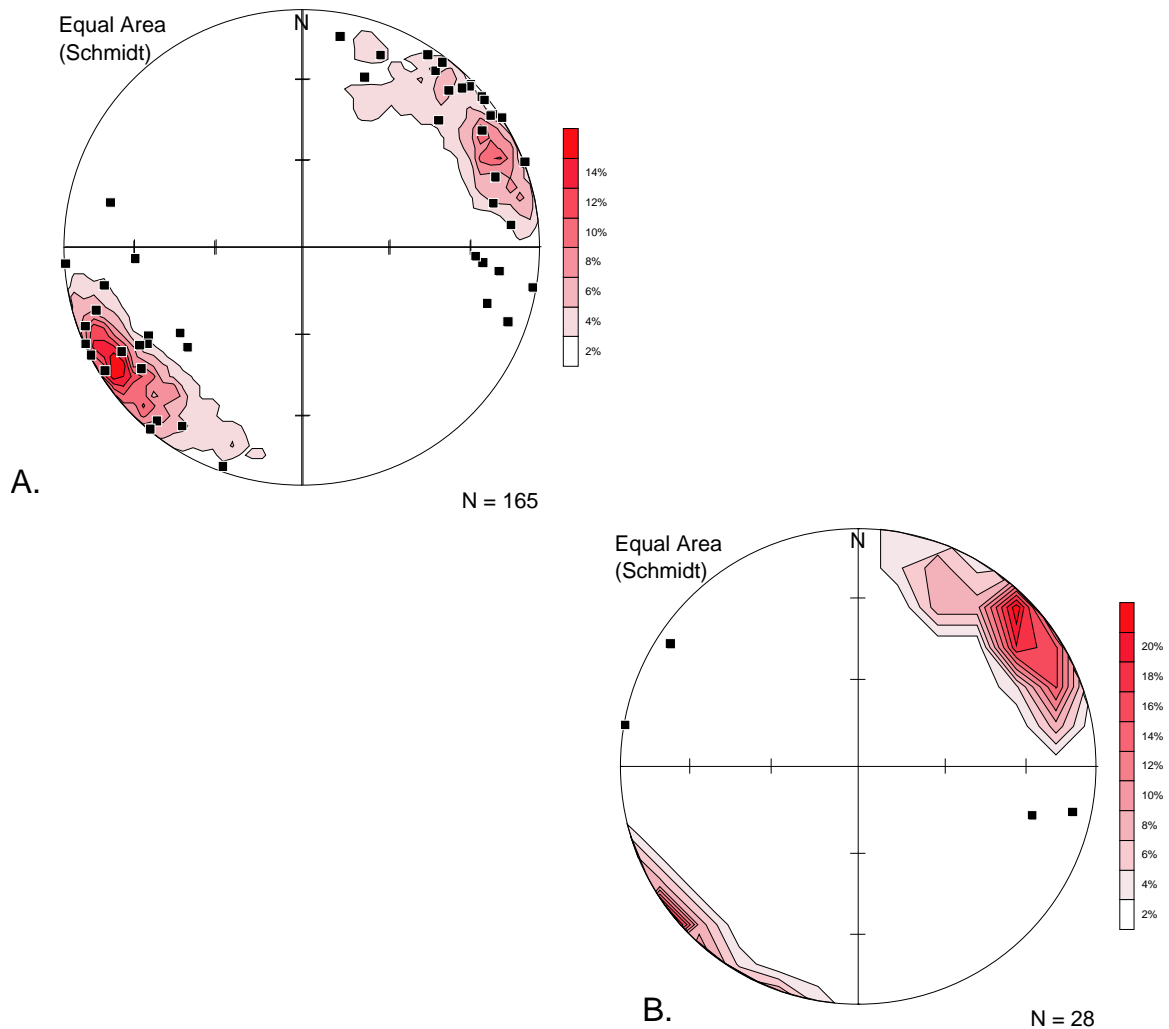
Figure 17 - Lower hemisphere equal area projections (intensity per 1% area) of contoured poles to S_2 foliation and axial-planes of F_2 folds (black squares). **(A)** Fault-block H. **(B)** Fault-block I. Overall pattern of steeply dipping foliation remain consistent between the fault-blocks, while the strike orientation becomes progressively more westward oriented in a west to east transect across the fault-blocks D – I. Overall pattern is again dissimilar to fault-blocks A – C.

due to intrusion of late pegmatites rather than intrusion of the Harney Peak

Granite. This portion of block C dominantly consists of micaceous schist, while

the northern portion is mostly medium- to thick-bedded metagraywacke. Thus,

the discontinuity of the Harney Peak Granite overprint may be related to

differential rheologic susceptibility of the two rock lithologies. Fault-blocks D

through I display S_2-dominated north-northwest trending, steeply dipping fabrics, whose strike directions vary only slightly from fault-block to fault-block but rotate systematically from NNW to NW moving eastward from D-I (Figures 15 to 17).

Folds

F_2 folds are the dominant ductile structures in the Mount Rushmore quadrangle. Outcrop-scale F_2 folds in fault-blocks D – I are characterized by tight to isoclinal folds that are vertical to steeply plunging and have axial planes that are approximately parallel to S_2 in the respective fault blocks. F_2 folds are generally northwest trending and have thickened hinges and attenuated limbs diagnostic of passive flow folds (cf. Ramsay, 1967). Fault-block B contains folds that otherwise resemble F_2 folds, but are tight to isoclinal and are recumbent. These folds generally lack a distinct S_2 foliation or S_2 is poorly defined, making them distinct from typical F_2 folds. Figures 12 and 13 illustrate typical outcrop-scale F_2 folds observed in the study area.

Map-scale F_2 folding is easily recognized on the published 1:250,000-scale map of the Black Hills (cf. Figure 7; Dewitt et al., 1986). A particularly good example is evident in the north-central portion of the Mount Rushmore quadrangle in the outcrop pattern of banded iron formations (Plate I; fault-block E). Other examples of F_2 folding are not especially well preserved in the map patterns, most likely due to translation and shearing along the many fault-zones. In the southwest portion of the quadrangle (fault-block A), the emplacement of the Harney Peak Granite has obliterated any evidence of F_2 folds.
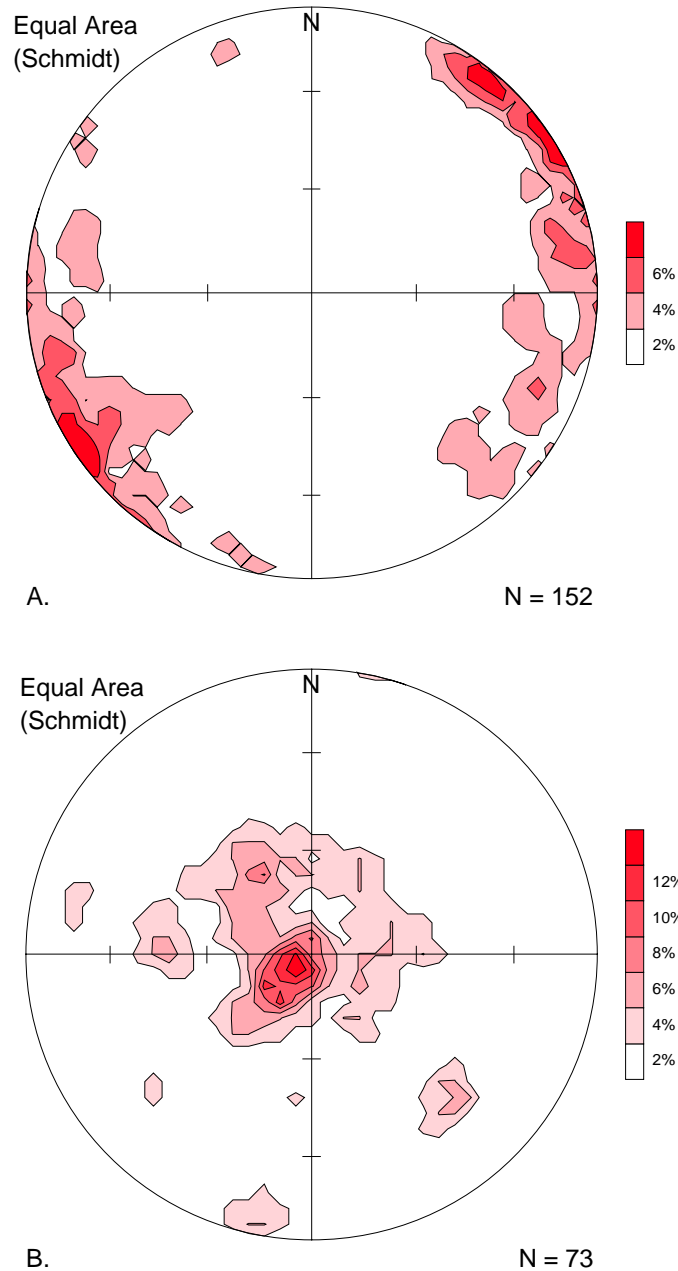
Figure 18 - Lower hemisphere equal area projections (intensity per 1% area) of poles to F_2 fold axial planes measured during this study. **(A)** F_2 folds in fault-blocks D – I. F_2 folds are northwest trending tight to isoclinal folds with steeply plunging hinge-lines. Axial planes are approximately parallel to the dominant S_2 foliation. **(B)** Tight to isoclinal, recumbent folds that otherwise resemble F_2 folds in fault-blocks A-C. These folds have shallowly plunging to horizontal hinge-lines and generally have a weak axial-planar fabric. They are similar to the fold shown in Figure 11. One interpretation is that these are early F_1 or F_2 folds that have been reoriented by the Harney Peak Granite intrusion. Regardless, these folds do not show the strong overprint of D_2 and later deformations and have experienced a different deformation history than the folds in fault blocks D – I.

Stereographic projections of F_2 fold data collected during this study are shown in Figure 18. Axial plane orientations by fault-block are also shown in Figures 15, 16, and 17. The F_2 folds in fault-block B have shallowly plunging to horizontal hinge-lines and generally have a weak axial-planar fabric. They are similar to the fold shown in Figure 11. One interpretation is that these are early F_1 or F_2 folds that have been reoriented by the Harney Peak Granite intrusion. Regardless, these folds do not show the strong overprint of D_2 and later deformations and have experienced a different tectonic history.

Lineations

L_2 lineations are the most prevalent linear fabric observed in the Mount Rushmore quadrangle. Fabric diagrams of L_2 lineations are shown in Figures 19 and 20. L_2's are generally intersection lineations between bedding/S_c and axial-planar foliation (S_2) that are parallel to the hinge-lines of the steeply plunging F_2 folds (Figure 17) and lie within the plane of S_2. L_2 lineations may also be defined by elongated minerals such as quartz and biotite in certain lithologies. Elongate quartz pebbles with long axes oriented in the L_2 direction are also recognized in certain mica-schists. Figure 21 shows an excellent example of L_2 defined by elongate quartz rods. This quartz mineral lineation appears to be both an intersection lineation and an elongation lineation. Based on the concentrated distribution of elongation lineations, the eastern part of the study area must have undergone considerable constrictional strain, resulting in LS-tectonites in some domains. However, in other areas the fabric is dominantly an SL-tectonite that
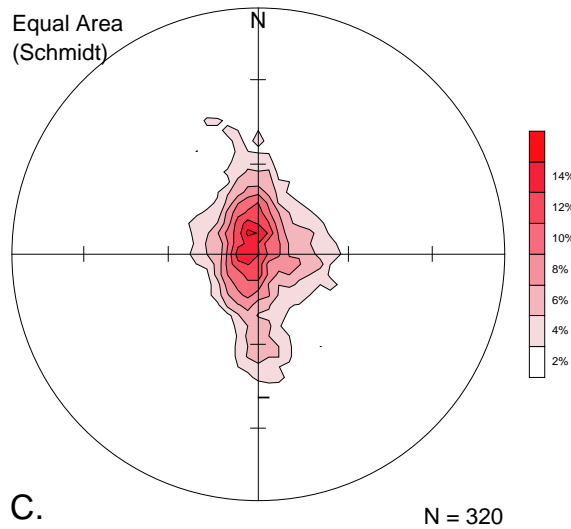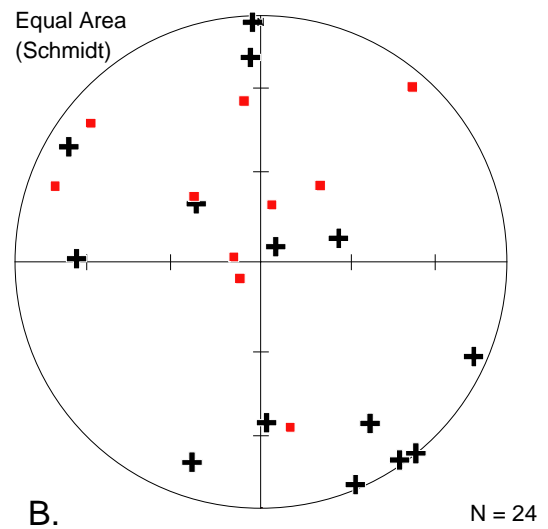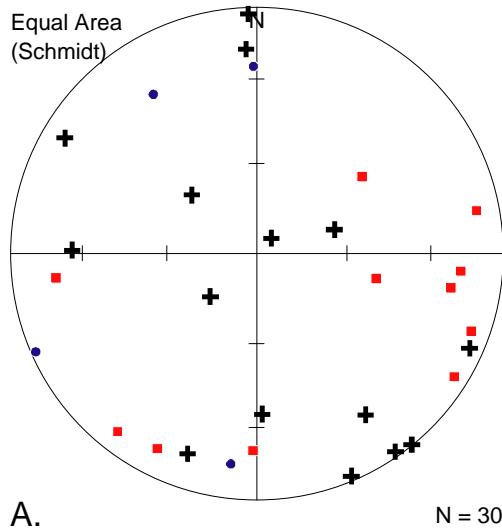
Figure 19 - Lower hemisphere equal area projections of L_2 lineations and F_2 hinge-lines measured during this study. **(A)** L_2 data for fault-blocks A (blue circles), B (red squares), and C (black crosses). **(B)** L_2 (black crosses) and F_2 hinge-lines (red squares) for fault-block C. **(C)** Contoured (intensity per 1% area) projections of L_2 lineations and F_2 hinge-lines for fault-blocks D – I. Note the agreement of L_2 and F_2 hinge-lines indicating that L_2 in fault-blocks D – I lie in the S_2 plane. Comparison with figure 18b suggests that the majority of the lineations for fault-block B are parallel to the hinge lines of recumbent folds.

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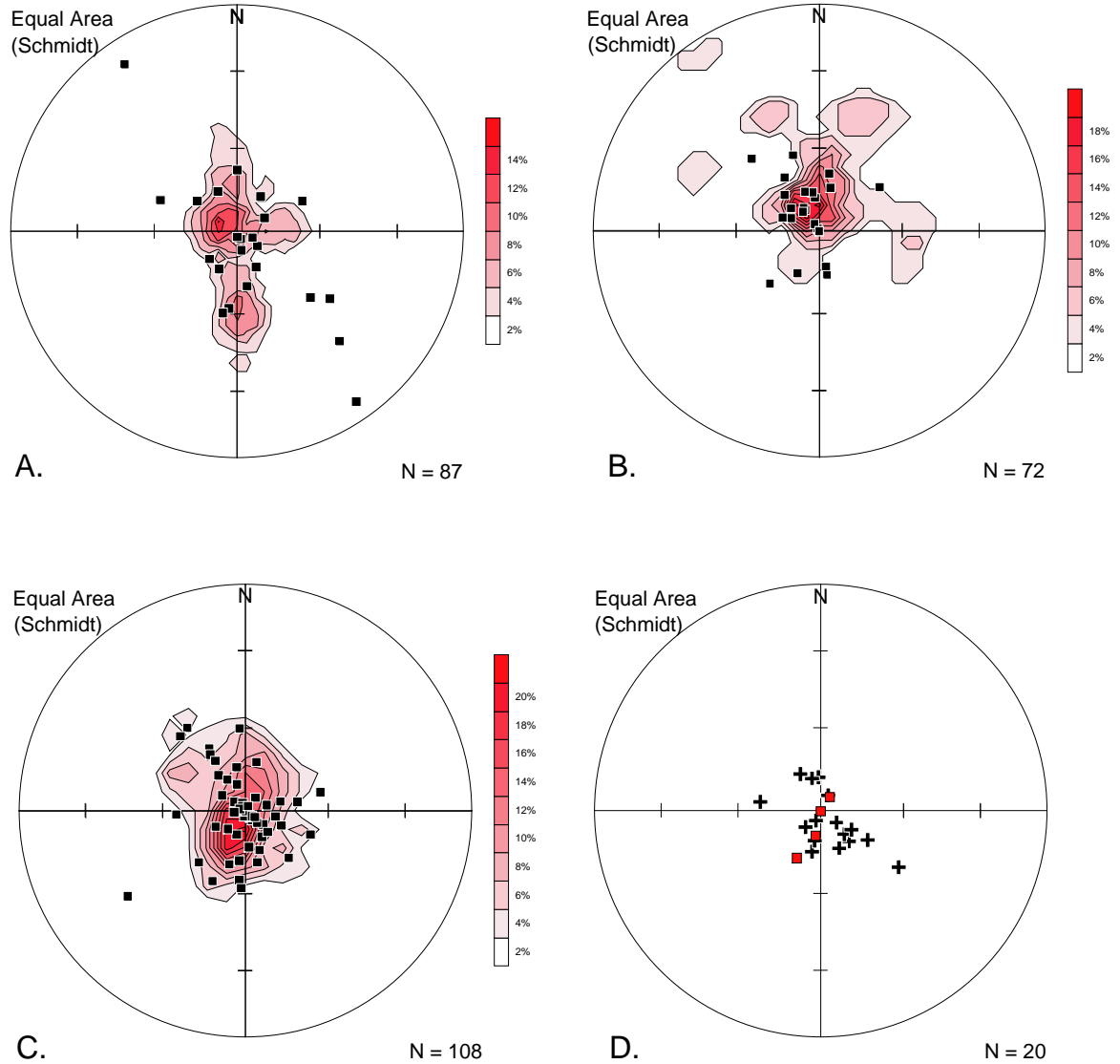
Figure 20 - Lower hemisphere equal area projections (intensity per 1% area) of L_2 lineations (contoured) and F_2 hinge-lines (black squares). **(A)** Fault-blocks D and E. **(B)** Fault-blocks F and G. **(C)** Fault-block H. **(D)** Fault-block I (L_2 = black crosses; F_2 hinge-lines = red squares). Note that orientations of L_2 and F_2 hinge-lines become more parallel from west to east across the fault-blocks.
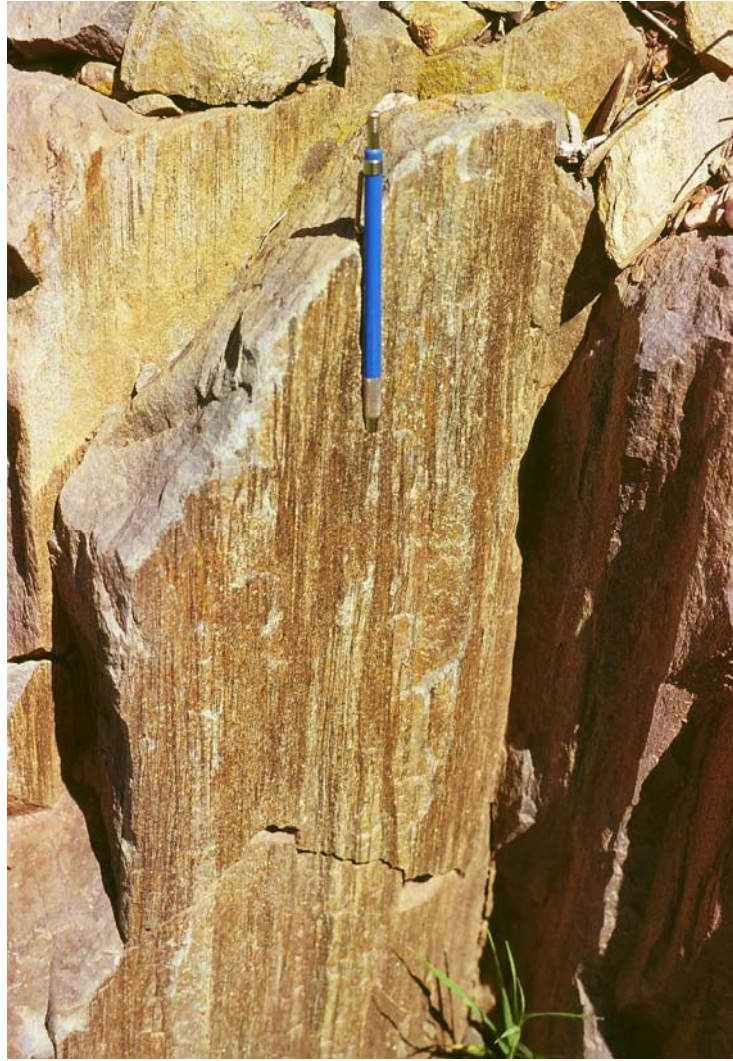
Figure 21 - Excellent example of L_2 lineations defined by elongate quartz minerals in quartz-mica schist. Note the vertical orientation of the L_2 lineations on this surface. The orientation of these lineations is identical to the S_c-S_2 intersection. Picture from same locality as Figures 12 and 13. Pencil is 14 cm long. See text for explanation.

results in prominent intersection lineations between the S-component of the

fabric and compositional banding or bedding. In general, the L_2 mineral

lineations appear to have developed by elongation parallel to the F_2 fold axes.

Variation of D_2 Deformation Features by Fault Block

Deformational features vary among the fault-blocks of the Mount Rushmore quadrangle. Fault-blocks A and B show markedly different deformational features from fault-blocks D – I, and from each other. Fault-block C shows deformational features that range in orientation from those in fault-block A to those in fault-blocks D – I. Fault-block A is dominated by the deformational and metamorphic overprint of the Harney Peak Granite (discussed below). Any earlier fabrics that may have existed in fault-block A have been transposed (Figure 15). It is not clear to what extent earlier fabrics may have been present. Fault-block B contains two fabrics, original bedding and a weak to moderately developed cleavage, which is axial planar to recumbent to reclined isoclinal folds (e.g. Figure 11). I interpret these folds to be F_2 folds that were subsequently reoriented and flattened by the emplacement of the Harney Peak Granite. Strong S_2 fabrics are not developed in this block and lineations are subhorizontal and parallel the hinge-lines of the F_2 folds (cf. Figure 15b).

Block C shows dominantly S_2 fabrics but is locally overprinted by Harney Peak Granite-related deformation where late pegmatites have intruded the local country rocks. S_2 fabrics in fault-block C are slightly less steeply dipping than S_2 in fault-blocks D – I and show correspondingly more scatter (Figures 15 – 20). The dominant S_2 fabric strikes slightly west of north and dips steeply northeast. A subset of the S_2 fabric strikes more westerly and dips variably to the north. F_2 folds and L_2 lineations are likewise variable within fault block C. In general, F_2 axial planes and the S_2 fabric show similar scatter (Figure 15c). However, the

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three concentrations of contoured poles to S_2 foliation represent the two limbs of

F_2 folds and reorientation of S_2 fabrics by Harney Peak related deformation. L_2

lineations and F_2 fold hinge-lines show tremendous variability in orientation within

fault-block C (Figure 19a, 19c). I attribute this variability of D_2 features to the

transitional nature of deformation in fault-block C. For instance, early formed D_2

features may have been variably reoriented by late stage pegmatite bodies. In

fact, most Harney Peak related deformation in fault-block C is concentrated

around localized pegmatite bodies in the southern portion of the fault-block.

Another possibility is that the variation in D_2 deformational features within

fault-block C was caused by the intrusion of the Harney Peak Granite. If the

Harney Peak Granite was being forcefully emplaced, and assuming that fault-

block C has had very little strike-slip movement post intrusion, one would expect

to see a north-striking, shallowly dipping reorientation of S_2. Any intrusive bodies

postulated underneath the southern half of fault-block C should show similar

reorientation of S_2 as shown in fault-block A. It is difficult to envisage how

emplacement of an intrusive body immediately west of rocks containing west-

striking fabrics (S_{2a} discussed below) could account for the generation of these

fabrics. The two subsets in the S_2 fabric could represent the incomplete

transposition of early S_2 fabrics, with the more westerly (group 2, Fig. 15c)

striking being the earliest fabric, S_{2a}, and the steeply northeast dipping, more

northwest striking subset (group 1, Fig. 15c) representing late S_{2b} development

and transposition of S_{2a} during oblique convergence, as discussed below.

Incomplete transposition of S_{2a} fabrics within fault-block C could have been accommodated by variation in localized strain partitioning during D_2.

Fault-blocks D – I show dominant D_2-related deformational features, although the orientation of these features vary somewhat among the fault-blocks. Despite the slight variation of S_2 among fault-blocks D – I, the overall pattern remains very similar. The steeply dipping foliation remains consistent between fault-blocks, while the strike orientation becomes progressively more westward oriented in a west to east transect across fault-blocks D – I. In all fault-blocks, S_2 is generally consistent with F_2 axial planes with the exception of fault-block I (Figures 16 and 17). Likewise, L_2 lineations and F_2 hinge-lines are consistent in all fault blocks (Figures 19b, 20). The pattern of fault-block E demonstrates a map-scale F_2 fold that is evident in the quadrangle. From west to east, the fault blocks show progressively stronger linear fabrics as shown by the stronger correlation between L_2 and F_2 hinge-lines.

Faults

Six major faults have been identified in the Mount Rushmore quadrangle (Figure 5). Multiple smaller fault-zones exist but were not mappable at the scale of this study, were not extensively traceable, or have little discernable displacement (Figure 22). The major faults trend north-northwest across the study-area, roughly parallel to the S_2 foliation. From southwest to northeast the faults are: Elk Mountain, Empire Mine, Keystone, Silver City (aka Silver Mtn), Echo Peak, and Storm Hill.

The Echo Peak fault separates fault-block F from fault-block H and separates quartz-mica schist from staurolite bearing quartz-mica schist. It is named herein for its exposure at the summit of Echo Peak. The Echo Peak fault is correlative with an unnamed fault first recognized southeast of the Mt. Rushmore quadrangle in the Rapid City West quadrangle by Dheeradilok (1974). The major faults are vertical to subvertical (Figure 23). The Empire Mine, Keystone, and Silver City faults are also characterized by the presence of graphite.
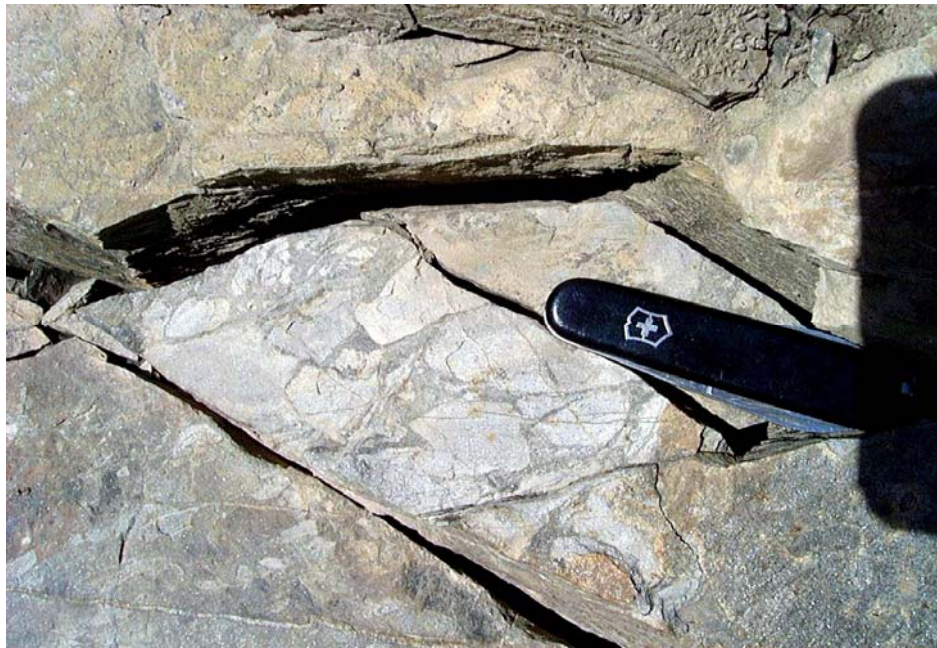
Figure 22 - Breccia in quartzite formed during early(?) brittle faulting in the study area. Late brittle faulting (Laramide) also occurred in the study area as the Black Hills were uplifted. Knife is 9 cm long.

Displacement and sense of movement along the majority of the faults are generally indeterminate because of the lack of appropriate marker units and other shear sense indicators. However, where recognized, shear sense indicators (e.g. Figures 24, 25, and 26) give an overall left-lateral sense of

Figure 23 - (A) Expression of the Keystone Fault in metagraywackes approximately 1.5 km west of the Keystone "Wye" on the north side of US16. Note silicified zone on left of photograph. **(B)** Same as A with overlay showing extent of fault zone. Note the vertical nature of the fault zone. My wife, Kristin, in the foreground for scale. She is 170 centimeters tall. View to NNW.
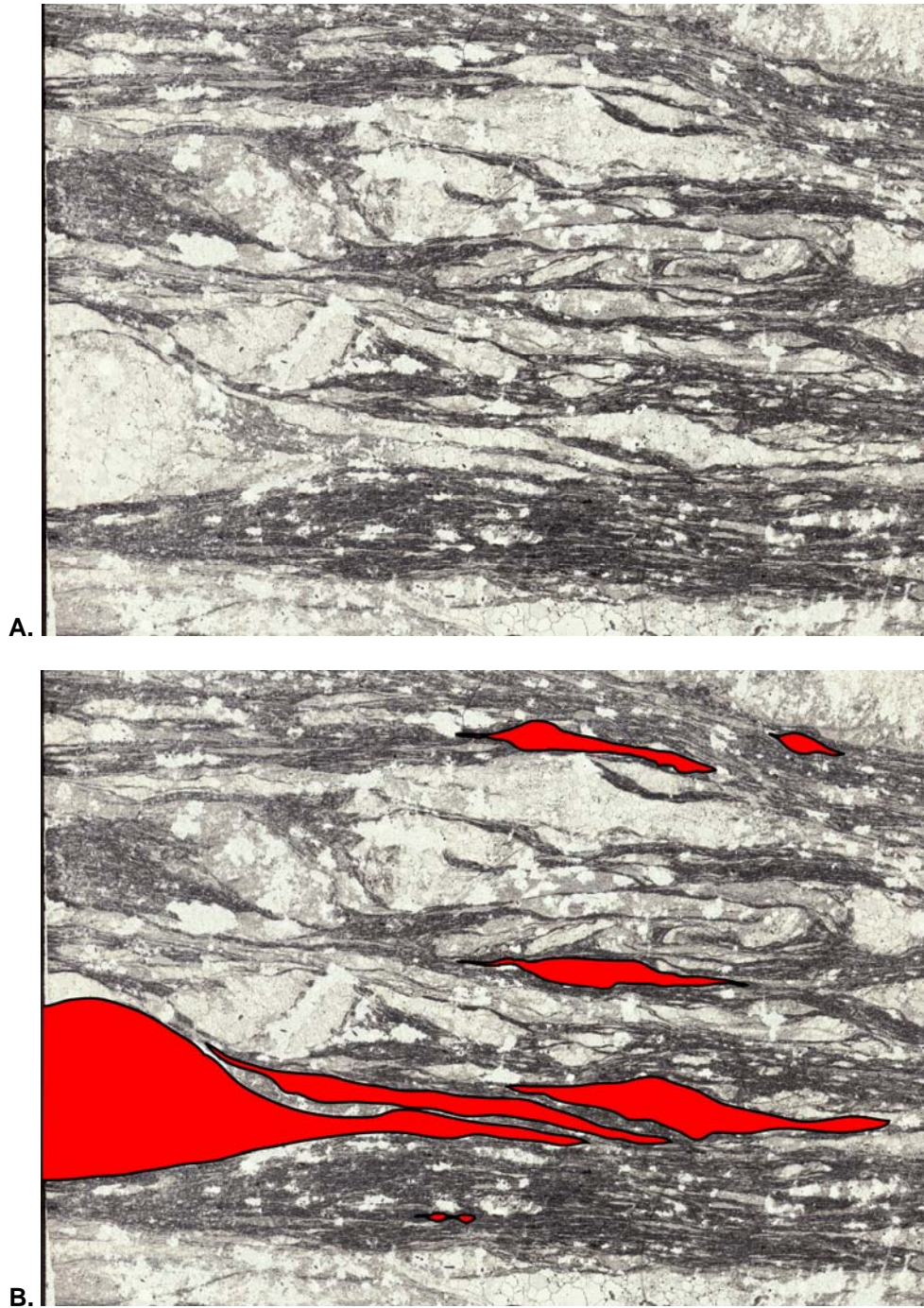
Figure 24 - (A) Photomicrograph of graphitic rocks from station MR270 showing left-lateral shear as defined by the asymmetry of the porphyroclasts. This sample was taken from the transition zone between the Empire Mine and Keystone faults. **(B)** Overlay of A outlining some of the more asymmetrical porphyroclasts. Note folded quartz layers in right-center of the photomicrograph. Field of view is approximately 3.5 x 6 mm.
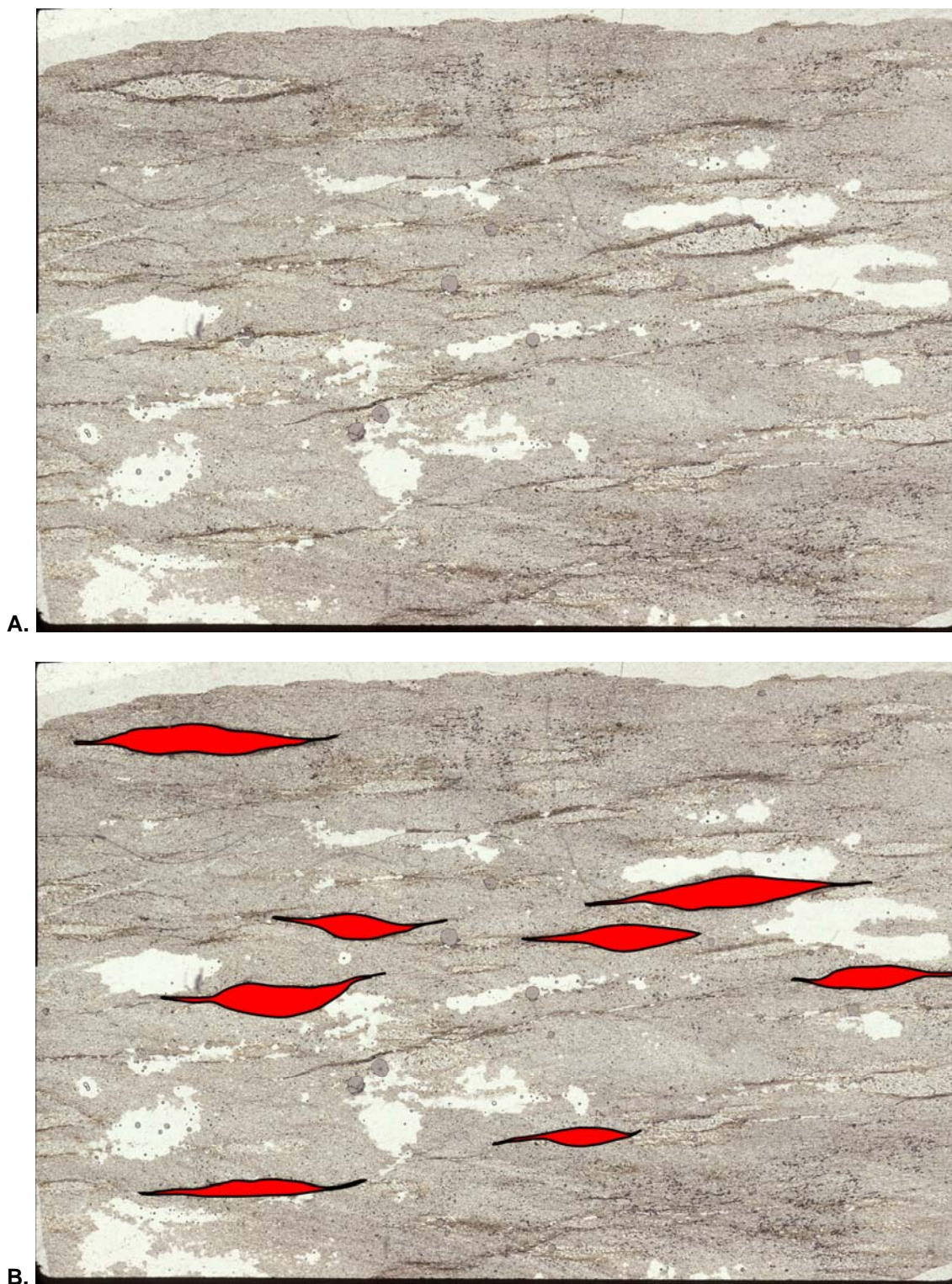
Figure 25 - (A) Photomicrograph of graphitic metasiltstone from station MR349 demonstrating left-lateral shear as defined by the asymmetry of the mica-quartz aggregates. Field of view is standard thin-section size (27 x 46 mm). **(B)** Overlay of A outlining the mica-quartz aggregates.
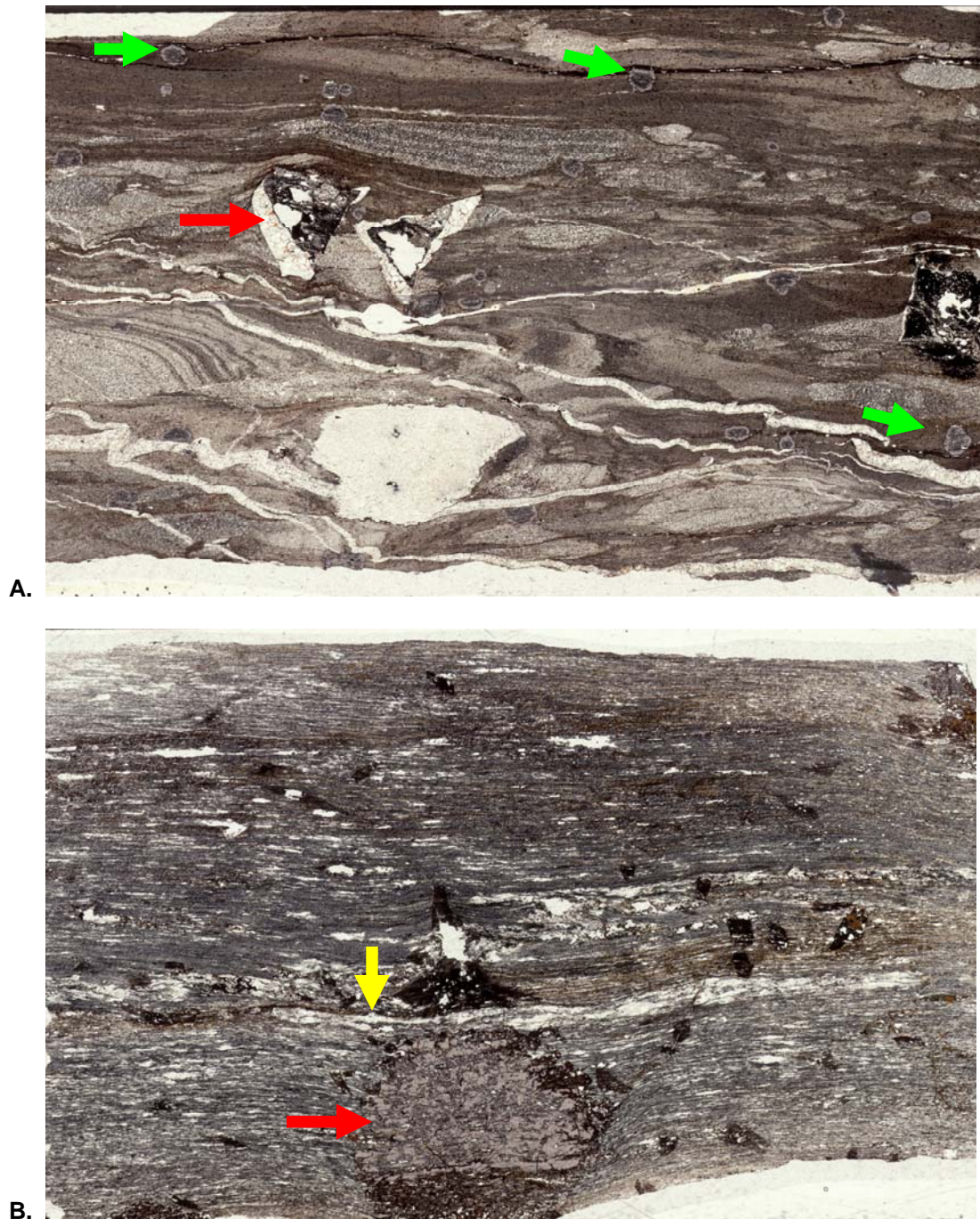
Figure 26 - (A) Photomicrograph of sample MR675, a sheared metapelite collected near the Silver City fault in fault-block H. Note the intense shearing and included garnets (green arrows) with clear rims indicating two-stage growth or change in growth conditions. Late staurolite porphyroblasts (red arrow) overgrow the dominant foliation in the center of the photograph. **(B)** Photomicrograph of MR733 in the Silver City fault zone. Note the complete transposition of earlier fabrics in B. The late skeletal garnet (red arrow) in B is overgrowing the transposed foliation and the thin-section is graphite rich. Quartz-rich layers above the garnet are shear-folded (yellow arrow). Field of view is 27 x 46 mm for both A and B.

movement parallel to the dominant S_2 foliation. Moreover, the overall map

pattern along the eastern edge of the Precambrian Black Hills indicates an

overall pattern of strike-slip faulting that is especially evident in the metabasites

and related rocks (cf., Figure 7).

Evidence presented in this study indicates that major faulting was initiated

prior to the emplacement of the Harney Peak Granite during the later stages of

D_2 deformation. Based on cross-cutting relationships, faults recognized in the

eastern part of the study area must be younger than similar structures west of the

study area, which have been deformed by the Harney Peak Granite (e.g. Hill City

fault, Grand Junction fault, Burnt Fork fault) (Figure 27). Overgrowth of fault

zones by late M_2 porphyroblasts (Figure 26) also indicate that major faults

predate the emplacement of the Harney Peak Granite.

Recognition of a Major Structural Discontinuity

A major structural break exists along the north-eastern boundary of fault-

block C (Keystone fault; Figure 27) across most of the Mount Rushmore

quadrangle. In the south central portion of the quadrangle, the Keystone fault is

bifurcated (Plate I). This bifurcated zone is an area of intense deformation.

Multiple rock types are juxtaposed along the 3 km length of this zone. The rocks

are heavily altered and are extremely graphitic in much of the zone. Rock types

include quartz-mica schists, graphitic schists, banded-iron formations, and

quartzite. Along the west-central portion of the study area, the structural

discontinuity is marked by the Empire Mine fault as displacement is seemingly

transferred from the Keystone fault to the Empire Mine fault. The Empire Mine

fault shows progressively more deformation to the northwest as the Keystone

fault shows correspondingly less deformation. Along the western boundary of

the quadrangle, the Empire Mine fault shows areas of intense deformation and

alteration similar to that along the more southern portions of the Keystone fault

described above. The Empire Mine fault continues northwest into the Hill City

and Silver City quadrangles where it truncates all earlier structures (Figure 27).

The overall sense of movement along the structural discontinuity is sinistral (cf.,

Figure 24). The direction of movement is constrained by C- and S-type shear

band cleavages, offset of lithologic marker units (Plate I), the asymmetry of veins,

and sheared porphyroclasts adjacent to the fault zone (Hill et al., 2004).   The

overall pattern of mapped faults in the eastern part of the Precambrian Black Hills

also supports an overall strike-slip motion (cf. Figure 7). This pattern is

especially evident in the offset of metabasalts, amphibolites, and metagabbros

mapped in the northeast Black Hills. Nabelek et al. (*in press*) have also

demonstrated that the regional M_1 biotite metamorphic isograd is more or less

coincident with the trace of the Silver City fault (Figure 6). This suggests that the

Silver City fault offsets regional M_1 metamorphic isograds, again indicating

significant displacement along the Silver City fault.

It is clear that the faulting along the eastern portion of the Black Hills must

be younger than that in the south-central portion west of the Empire Mine fault

based on cross-cutting relationships. The Empire Mine-Keystone faults truncate

all other structures indicating that faults to the east are younger. Folding of the
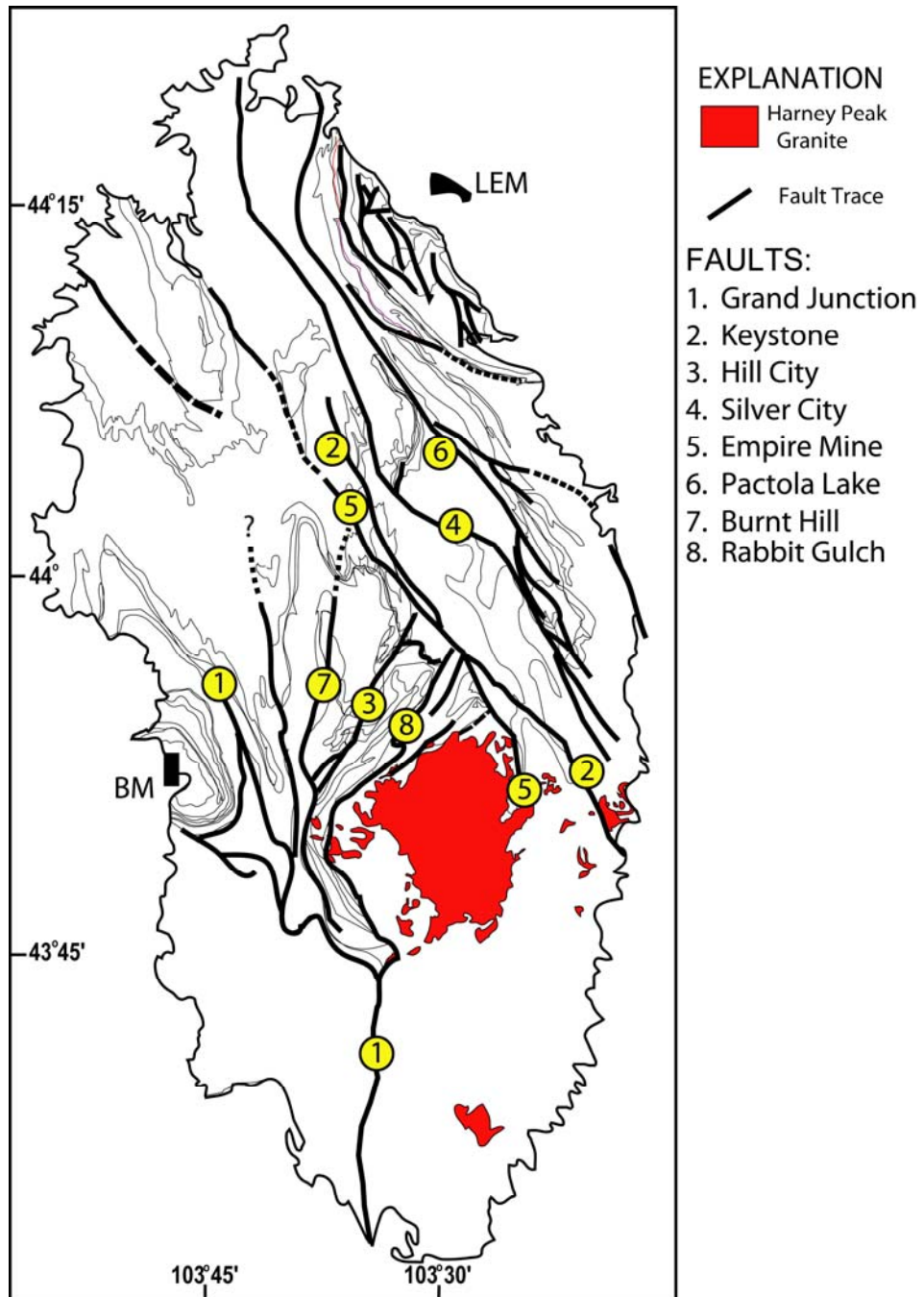
Figure 27 - Outline map of the Precambrian Black Hills uplift showing locations of major faults mentioned in this study. Note that the Empire Mine-Keystone faults truncate all other structures indicating that faults to the east are younger. Also note the folding of the Grand Junction and Hill City faults by the Harney Peak Granite suggesting that the intrusion post-dates faulting to the west. Compare with Figure 7.

Grand Junction and Hill City faults by the Harney Peak Granite suggests that the intrusion post-dates faulting to the west of the intrusion. (Figure 27; cf. Dewitt et. al, 1986). What remains unclear is whether any of the faults are related to the D_1 event. Folded faults that follow lithologic contacts would suggest a D_1 relationship. However, the intrusion of the Harney Peak Granite as a late syn- to post- deformational pluton has also resulted in folding of faults in the central Black Hills. Nabelek et al. (*in press*) favor late syn-deformational intrusion of the Harney Peak Granite and uplift along the Hill City and Empire Mine-Keystone fault systems based on precipitation of graphite along the fault zones, secondary fluid inclusion data, and overall structural discontinuity along the bounding faults of the Harney Peak block.

My observations indicate that most major faults in the Black Hills are related to the D_2 deformational event and that the D_2 event encompasses both the "Black Hills" and "Dakotan" orogenies of Chamberlain et al. (2002). Approximately 50 million years separate the two "orogenies" based on published age data (e.g., Dahl et al., 1999 a,b; Chamberlain et al., 2002; Dahl et al., 2005a,b). As such, they can be thought of as a single, protracted event, which I have divided into D_{2a} and D_{2b} phases. D2a resulted in the north-directed thrusting and early folding and faulting. D2b structures formed as collision became progressively transpressive. With respect to this nomenclature, faults like the Grand Junction fault and the Hill City fault are related to D_{2a} while the Empire Mine-Keystone fault and all faults east of the structural break are related to D_{2b}. A tectonic model using this nomenclature and its relationship to

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structures found in the Mt. Rushmore quadrangle and in the eastern Black Hills is discussed in greater detail later in this study.

D_3 Deformation

D_3 deformation was not recognized in the study area, but is recognizable from outcrop patterns north of the Mt. Rushmore quadrangle in the Silver City, Deerfield, and Pactola Reservoir quadrangles (Redden et al., 1990; Redden et al., 2005; Redden, unpublished mapping). Noble et al. (1949) recognized F_3 folds in the Homestake mine area and referred to them as "cross-folds". F_3 folding affects much of the central Black Hills (Redden et al., 1990). F_3 folds are doubly plunging folds that refold F_2 folds (Redden et al., 1990). Redden (Redden et al., 1990; Redden, 2001, pers. comm.) describes these folds as "cross-folds" or "porpoises." These folds are not common in the southern Black Hills, but may be recognized on more detailed maps north of the Mount Rushmore quadrangle. Dahl et al. (1998) suggested that renewed convergence along the southern margin of the Wyoming craton may have produced these folds. They are generally restricted to single fault-blocks and are oriented somewhat obliquely to the bounding faults.

An alternate possibility is that these F_3 "cross-folds" represent *en echelon* arrays of folds formed as subsidiary structures during strike-slip movement of the bounding faults. The acute angle between the F_3 cross-folds and the bounding faults would indicate the direction of movement for the adjacent fault-blocks, which based on unpublished mapping of Redden (pers. comm.) is consistent with overall sinistral translation of the fault-bounded blocks. F_3 folds could also

represent shear or possibly drag folding of earlier F_2 folds during translation of the containing fault-blocks. Fabric data collected in fault-block B may also support the idea of shear folding during translation of the fault blocks that resulted in F_3 cross-folds. Measured S_0 and S_c attitudes within fault-block B record markedly different structural trends based on their location with respect to the trace of the Empire Mine fault (Figure 28). Those attitudes taken closest to the fault have a mean principal orientation of 285/58 and a beta axis of 05/102, while attitudes taken away from the fault have a mean principal orientation of 034/65 and a beta axis of 01/214. This difference may reflect a counter-clockwise rotation (i.e. drag folding) of material closest to the fault zone during left-lateral strike-slip movement along the Empire Mine fault.

D_4 Deformation

D_4 deformation is primarily restricted to fault-block A, which contains the Harney Peak Granite, and the immediately adjacent southern half of the east-adjacent fault-block C (Figures 5 and 6). D_4 is associated with the intrusion of the Harney Peak Granite. Multiple pegmatites of varying size (one meter or less) intrude the country rocks over the southern third of the Mt. Rushmore quadrangle, but only locally deform the country rocks. The main body of the Harney Peak Granite and its satellite plutons occupy an area of roughly 100 km^2 in the south-central Black Hills. The mechanisms of emplacement of the main Harney Peak Granite have been inferred by analogy from the study of one of its smaller satellites (~1 km^2), the Calamity Peak pluton (Duke et. al, 1988). The

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model suggests that the Harney Peak Granite consists of multiple pulses of genetically related magma that were initially discordant sills fed by concordant feeder dikes. Each successive pulse was injected forcefully along the upper contact between pre-existing granite layers and the country rock. Continued growth by forceful injection resulted in ballooning of the granite and upward and outward growth of the granite and produced an overall dome-shaped structure of the Harney Peak Granite and associated D_4 fabrics.

Foliation

The forceful emplacement of the Harney Peak Granite resulted in a roughly concentric fabric (S_4) adjacent to the pluton, strong crenulation cleavages, and transposition of all earlier fabrics (Figure 29; c.f., Figure 15a). Note the overall similarity of S_4 to reoriented S_2 fabrics. S_4 fabrics generally show variably developed D_4 structures such as a spaced or crenulation cleavage that overprint D_2 deformational features as a result of forceful emplacement of the Harney Peak Granite. The two maxima in this diagram likely represent the change of S_4 orientation along the curved periphery of the Harney Peak Granite. The pattern looks very similar to that of fault-block B (Figure 15b) indicating that the Harney Peak Granite is flattening earlier F_2 folds in fault-block A.

The southern portion of fault-block C immediately adjacent to the Harney Peak block also shows some deformation that is likely associated with D_4. As discussed previously, the larger economic pegmatites that occur in this block and the occurrence of schists may account for the local deformation. Locally, smaller

A

Mean Principal Orientation = 034/65
Mean Resultant dir'n = 10-133
Mean Resultant length = 0.61
(Variance = 0.39)
Calculated.girdle: 304/89
Calculated beta axis: 1-214

Principal Eigenvector: 25/304
(i.e. normal to plane dipping: 65/124)
Mean Direction: 80 - 313
Mean Resultant = 0.606
('Variance' = 0.394)
E2-E3 (girdle) plane: 89/034

                (Normalised)
 Eigenvectors   (Eigenvalue)
-0.828 -0.561 0.010 (0.012)
-0.233 0.361 0.903 (0.439)
0.510 -0.745 0.429 (0.549)
Shape parameter, gamma = 0.06
Strength parameter, zeta = 3.80
Eigenvalue log ratios:
(E2/E1 | E3/E2)
3.58 | 0.22

B

Mean Principal Orientation = 285/58
Mean Resultant dir'n = 34-026
Mean Resultant length = 0.61
(Variance = 0.39)
Calculated.girdle: 192/85
Calculated beta axis: 5-102

Principal Eigenvector: -32/195
(i.e. normal to plane dipping: 58/015)
Spherical standard error: 0.344
95% conf.cone semi-angle: 36.50°
Mean Direction: 56 - 206
Mean Resultant = 0.612
('Variance' = 0.388)
E2-E3 (girdle) plane: 85/282

                (Normalised)
 Eigenvectors   (Eigenvalue)
-0.207 0.975 0.081 (0.131)
-0.535 -0.044 -0.844 (0.322)
0.819 0.218 -0.531 (0.547)
Shape parameter, gamma = 0.59
Strength parameter, zeta = 1.43
Eigenvalue log ratios:
(E2/E1 | E3/E2)
0.90 | 0.53

Figure 28 - Lower hemisphere equal area projections of poles to S_0/S_c foliation in fault-block B. **(A)** S_0/S_c measured away from the trace of the Empire Mine fault. **(B)** S_0/S_c measured in close proximity to the trace of the Empire Mine fault. Note that a counter-clockwise rotation of material closest to the fault could explain the difference and indicate possible initiation of drag folding not recognized in the field. See text for explanation.

pegmatites deform the rocks into which they are intruded but not on a large

scale. Elsewhere in fault-block C and all other fault-blocks, rocks are unaffected

by the emplacement of the Harney Peak Granite.
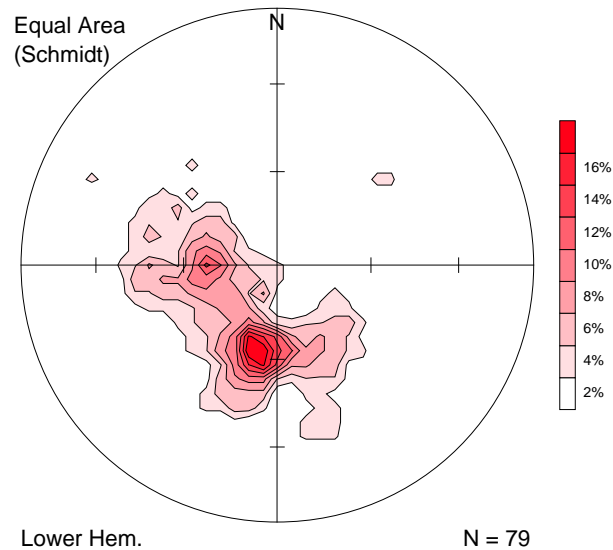
Figure 29 - Lower hemisphere equal area projection (intensity per 1% area) of poles to S_4 foliation measured in fault-block A.

Faulting

No evidence for distinct faults that can be directly related to D_4 was observed in the Mount Rushmore quadrangle. However, Nabelek et al. (*in press*) suggest that the Harney Peak block was uplifted along the Hill City and Empire Mine-Keystone faults based on the presence of late andalusite in the metamorphic aureole and the sharp difference in the dominant foliation. They suggest that the Harney Peak block was initially intruded by magma at a greater depth than its current relative position and was uplifted to its present structural level. Fluid inclusion data from pegmatites suggest late, low pressure deformation (Sirbescu and Nabelek, 2003), suggesting post-intrusive movement along the faults. At the very least, movement along the major fault systems

continued after the intrusion of the Harney Peak Granite (Hill et al., 2004;

Nabelek et al., *in press*).

D_5 *Deformation*

A post intrusion D_5 event, which produced a northeast-trending fabric

across the central Black Hills ca. 1535 Ma, was first suggested by Redden et al.

(1990), based on the slope of a bulk sample Rb-Sr isochron plot for whole-rock

samples of the Montana Mine formation and metagraywackes near the Three

Forks area, 8 km northeast of Hill City. Redden described locally recognizable

NE-trending D_5 related folds with a spaced axial-planar cleavage. Distlehorst

(1999) reported a weakly developed, northeast-southwest striking, spaced biotite

cleavage in the Rockerville area, west of the study area.

Foliation

In the study area, the D_5 event is recognized as spaced cleavage (S_5) or,

less commonly, as a late crenulation cleavage (Figures 30 and 31) that cross-

cuts the dominant S_2 foliation at a high angle. In the southeastern portion of the

study area, S_5 is a crenulation cleavage that progresses to a spaced cleavage to

the east. This crenulation was first recognized in the center of the quadrangle

east of the Silver City fault and may be seen in the road cuts north of US-16

beginning at the intersection of US-16 with the mapped trace of the Silver City

fault (Plate I). This crenulation cleavage (Figures 31 and 32) progresses to a

slaty cleavage eastward and is recognized as such by the eastern boundary of

the quadrangle. Because this fabric intensifies away from the Harney Peak

Granite, it is unlikely that it is in any way related to the intrusion. Microscopically,

D_5 may be recognized as either a spaced cleavage, defined by the orientation of

retrograde biotites or chlorite porphyroblasts, or less commonly as a crenulation

cleavage (Figures 33, 34).

Folds

One probable small-scale D_5 related fold was identified in the quadrangle

(Figure 35). This fold had an axial plane orientation of 020/81 with a plunge of

70/197. The measured S_5 foliation was not axial-planar to this fold with an

orientation of 212/66, although it appeared to be in the outcrop. The attitude of

this fold is consistent with described F_5 generation folding (e.g., Redden et al.,

1990). No other likely F_5 folds were recognized in the Mount Rushmore

quadrangle even though the S_5 fabric was evident over much of the southeastern

portion of the study area.

Summary of Deformational Events

Three major deformational events are recognized in the study area. Table

3 summarizes events recognized in this study and compares them to previous

studies. None of the fault-blocks in this study area exhibit every deformational

fabric. Fault-blocks A, B, and C show very distinct structural histories. Fault-

blocks D – I are similar with respect to each other but are markedly distinct from

fault-blocks A, B, and C. A major structural break exists along the
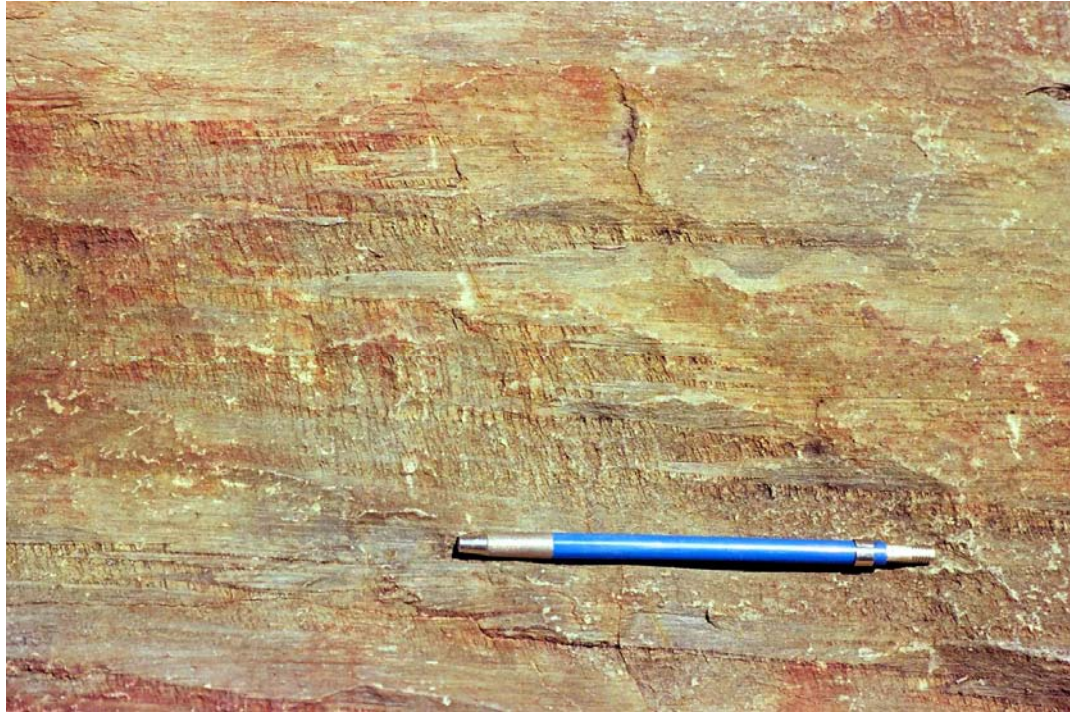
A.

B.

Figure 30 - Field photographs showing the well developed S_5 spaced cleavage and its relationship to the dominant S_2 fabric. **(A)** Photograph of S_5 recognized in the limb of a F_2 fold. S_5 closely spaced and is nearly vertical and S_2 is parallel to the pencil and trends left to right. Pencil is 14 cm long. **(B)** Photograph of wider spaced S_5 on the S_2 surface. S_5 trends left to right in the photograph and S_2 is nearly vertical. Knife is 9 cm long.
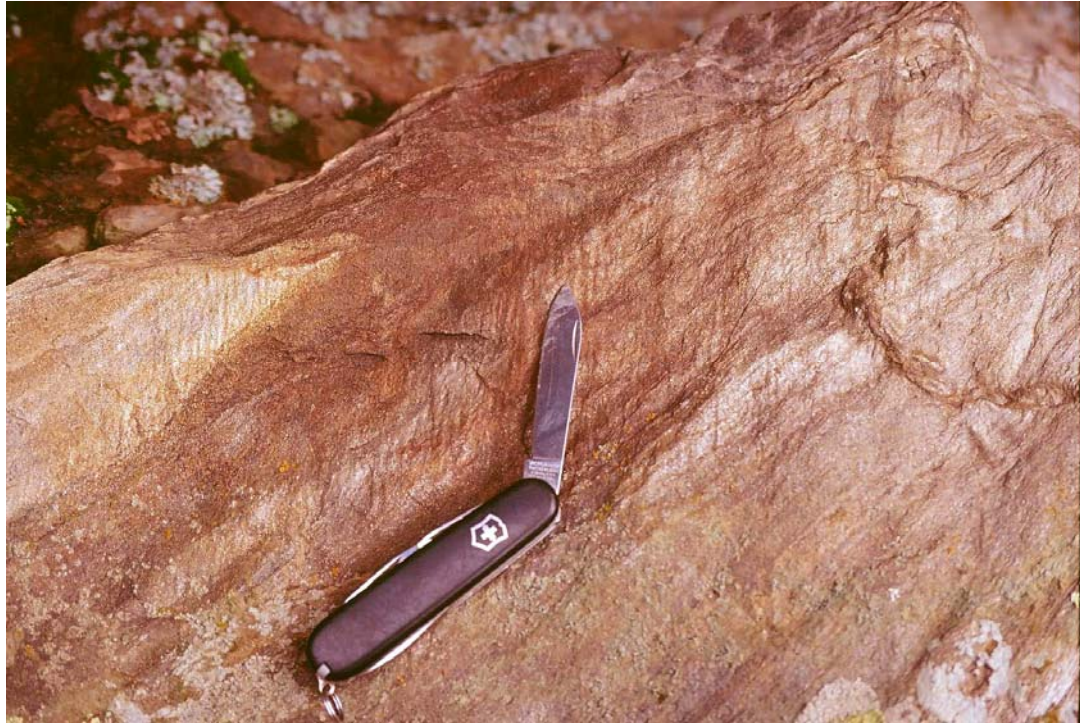
Figure 31 - (A) Field photograph of S_5 crenulation cleavage developed east of the Silver City fault. Knife body is parallel to S_2 (nearly vertical) and knife blade is parallel to S_5. S_5 is plunging steeply in the viewing direction. Body of knife is 9 cm long. Blade of knife is 7.5 cm long. **(B)** Spaced S_5 cleavage (trends bottom right to top left) cross-cuts S_2 foliation (nearly vertical and parallel to pencil). Pencil is 14 cm long.

A.

B.
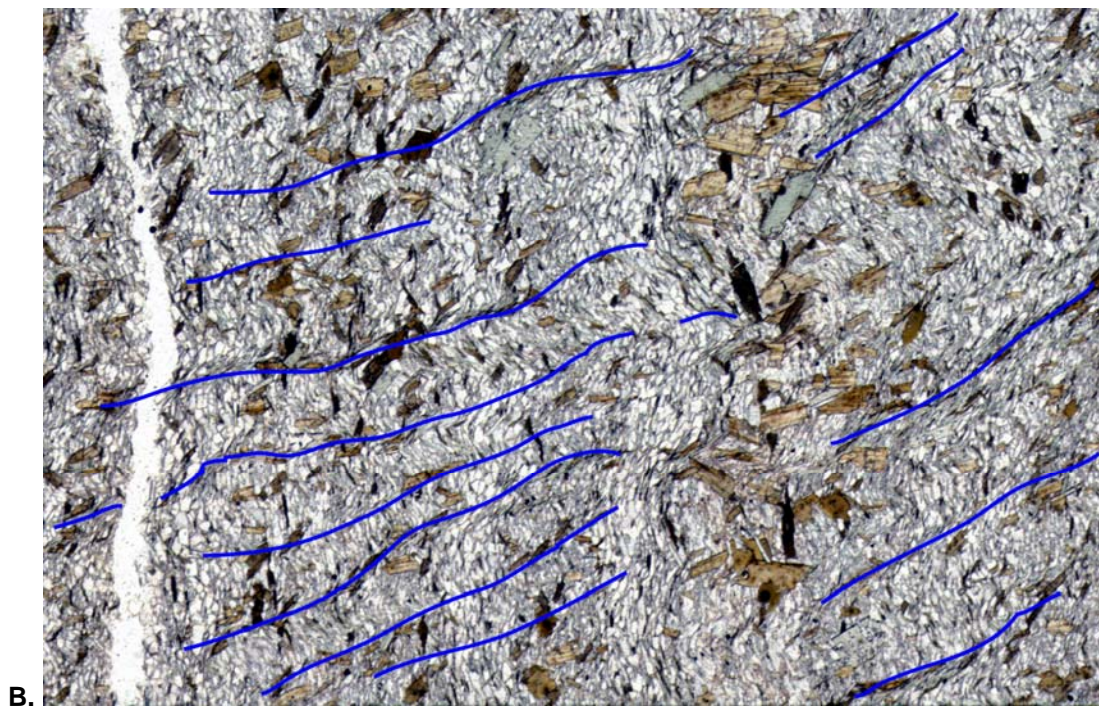
Figure 32 - (A) Photomicrographs of S_5 as defined by bounding surfaces of microlithons. **(B)** Overlay of E showing S_5 in blue. Field of view for photomicrographs A and B is approximately 1 x 1.5 mm. Thin section of sample MR945, fault-block F.
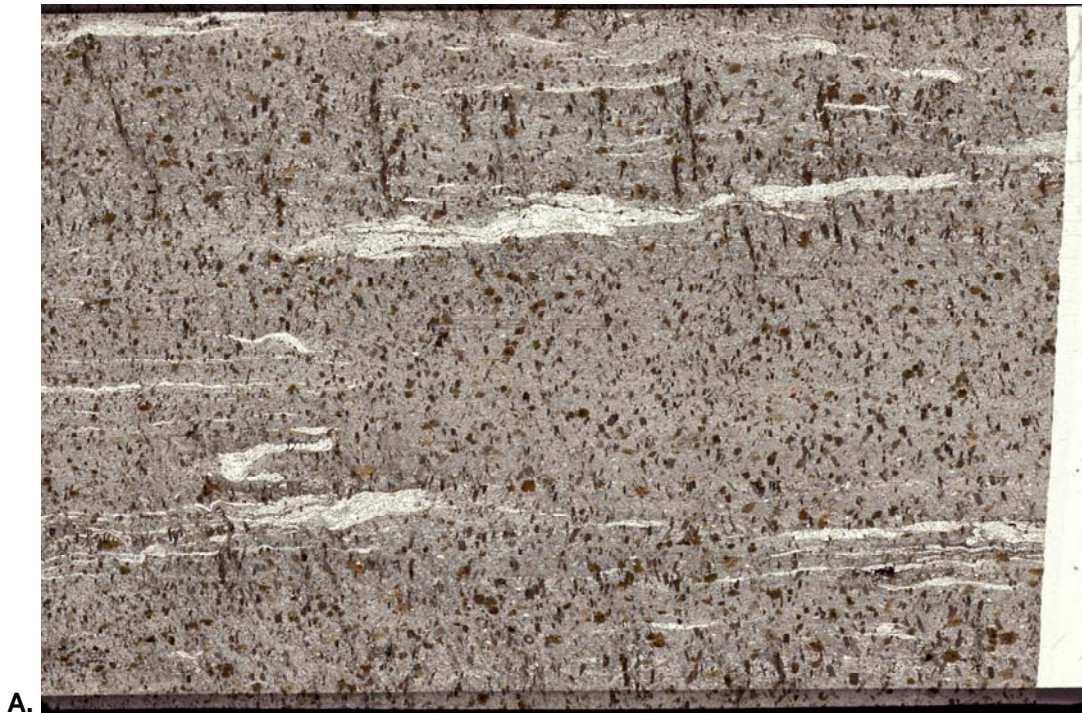
Figure 33 - Photomicrographs of S_5 foliation. **(A)** Sample MR932 showing distinct S_5 spaced cleavage (nearly vertical) defined by biotite selvages. S_2 is nearly horizontal. Note the folded and transposed quartz stringers that define the S_2 fabric. **(B)** Sample MR740 showing less distinct S_5 spaced cleavage and aligned chlorite porphyroblasts. S_2 is subhorizontal and defined by the preferred orientation of small, earlier biotites. Field of view is 27 x46 mm.
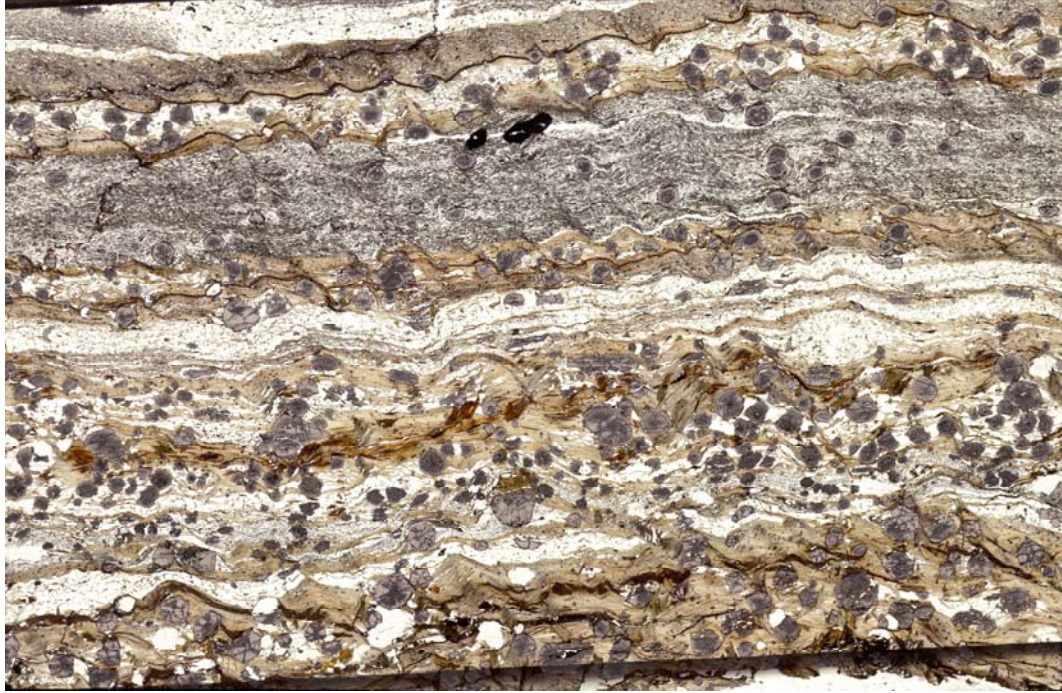
Figure 34 - Photomicrograph of sample MR915 showing well developed S_5 crenulation cleavage trending subvertically right to left. S_2 is subhorizontal. Field of view is 27 x 46 mm.
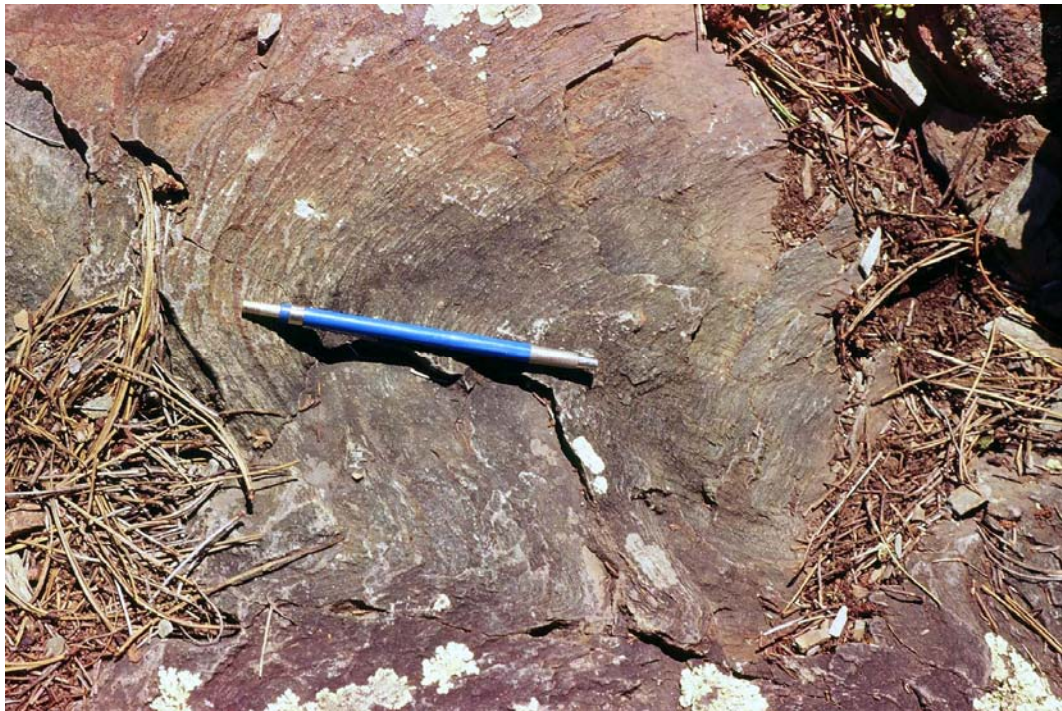
Figure 35 - Photograph of possible F_5 fold showing warping of S_2 foliation. A weak spaced foliation (S_5) is parallel to the pencil trending bottom right to top left. S_5 appears axial planar but dips in opposite direction. Pencil is 14 cm in length.

north-eastern boundary of fault-block C (Keystone fault) across most of the study area. Along the west-central portion of the study area, the structural discontinuity is marked by the Empire Mine fault as displacement is seemingly transferred from the Keystone fault to the Empire Mine fault (i.e., possible left stepover). The Empire Mine fault continues northwest into the Hill City and Silver City quadrangles where it truncates all earlier structures (cf. Dewitt et al., 1986; Figure 7). My observations are consistent with the assertions of Hill et al. (2004) and Nabelek et al., (*in press*) that fault-blocks in the study area and, by extrapolation, east of the structural break have differing structural and P-T histories.

TECTONIC OVERVIEW AND OBLIQUE CONVERGENCE MODEL

The history of the assembly of southern Laurentia is an epic involving multiple Archean and Paleoproterozoic landmasses undergoing simultaneous convergence along multiple margins. Although the current state of knowledge is adequate to decipher the relative timing of these events, much debate continues. Current and future research will undoubtedly refine both the absolute timing and tectonic history of southern Laurentia. Much work remains to be done and the tectonic synthesis presented herein is knowingly inadequate. It is beyond the scope of this paper to discuss in detail the tectonic history of southern Laurentia.

	Folds		Fabrics	Faults	
	Style	**Orientation**			*Remarks*
D_1					*not observed in this study
D_{2a}	Tight to isoclinal	Reclined to recumbent; NE trending	Early, weak axial-planar as observed in fault-block B; possibly related to observed compositional banding	Grand Junction, Hill City, Burnt Fork, and other faults west of structural break	*possible correlation with D_1 structures of Redden et.al (1990) and Dahl et. al (1998a)
D_{2b}	Isoclinal	North to northwest trending, upright to steeply plunging	Dominant S_2; steeply dipping, axial planar fabric	Empire Mine, Elk Mtn, Keystone, Silver City, Storm Hill; reactivation of Hill City(?)	*S_1 of Redden et. al (1990)
D_3		Possible drag folding along Empire Mine fault;			*Not observed in this study; F_3 of Redden et. al (1990) and "cross-folds" of Noble et.al (1949)
D_4	Tight to isoclinal	recumbent; reorientation of D_{2a} folds	Local schistosity and crenulation cleavage associated with granite emplacement; Restricted to fault-block A and southern, adjacent portion of fault-block C	Uplift along Empire Mine and Hill City faults (?); Elk Mountain fault; Golden Slipper and Rabbit Gulch brecciated zones (Ratte & Wayland, 1969)	* Uplift of entire Harney Peak block (Nabelek et. al, *in press*). Not an actual "doming" event caused by intrusion of Harney Peak Granite. Doming and S_3 of Redden et. al (1990).
D_5			Northeast trending crenulation and spaced cleavage in the southern portions of fault-blocks E, F, and H		*S_4 of Redden et. al (1990)

Table 3 - Revised summary of deformational events and related structures based on this study. Compare with Table 2.

My intention here is to provide sufficient knowledge to familiarize readers with the

tectonic framework of southern Laurentia, and thus to be able to discuss a

tectonic model for the study area and its broader implications.

Laurentian Assembly: Overview

J. Tuzo Wilson (1962) first advanced the idea of "mobilism" of Proterozoic orogenic belts exposed in the Canadian shield, providing the impetus to apply new techniques and concepts to the study of Precambrian rocks. Over the past several decades, much has been learned about the assembly and evolution of Laurentia. An excellent synthesis of geologic, geophysical, and geochemical data by Hoffman (1988, 1989) outlines the framework regarding Laurentian assembly. Figure 1 illustrates the generalized tectonic elements involved in the assembly. The assembly of northern Laurentia, where exposed in the Canadian shield, is relatively well understood as compared to that of southern Laurentia where parts of the shield are masked by Phanerozic cover.

In the southern portion of Laurentia, the 1.9- 1.83 Ga Penokean orogeny occurred along the southern boundary of the Superior Province and was the result of the accretion of one or more island-arcs formed over a south dipping subduction zone (e.g., Peterman et al., 1985; Sims and Peterman, 1986; Hoffman, 1988; Sims et al., 1989, 1993; Van Wyck and Johnson, 1997; Holm et al., 1998). The northern margin of the Superior Province records the 1.9-1.83 Ga Trans-Hudson orogeny that resulted from the collision of the Hearne-Rae Province with the Superior Province. Tectonic polarity for the orogen is interpreted on the basis of the internal zones of the orogen, with the Superior Province as the foreland and the Hearne Province as the hinterland. The term Trans-Hudson orogeny has also been used to refer to the 1780 – 1715 Ma east-west directed collision between the Wyoming and Superior provinces (e.g.,

Redden et al., 1990; Dahl et al., 1998, 1999 a, b, 2005a,b; Chamberlain et al., 2003), however, as discussed below, this designation may not be appropriate. The collision between the Wyoming Province and the Hearne-Rae Province to the north has historically been inferred to be pre-Trans-Hudson, however this interpretation is also equivocal and the discussion below reexamines this inference.

Incongruities with Laurentian Assembly

Although the basic framework is in place to recount the assembly of Laurentia, many problems and controversies still exist (Lewry et al., 1990; Machado, 1990; Boone and Hynes, 1990). The building of Laurentia involved at least six Archean microcontinents: Slave, Rae, Hearne, Wyoming, Superior, and Nain, which were sutured along multiple Proterozoic orogenic belts (Figure 1; Hoffman, 1988). Even in the Canadian shield where the Proterozoic belts are best exposed, complications arising from lack of good age constraints and imprecise structural relationships yield multiple viable interpretations of the same data (e.g. Hoffman 1990, Lewry and Collerson, 1990).

The complications in elucidating the assembly of Laurentia are most pronounced along the boundaries between the southern-most Archean components (Wyoming, Superior, Hearne provinces, and Medicine Hat Block), where the boundary zones are obscured by Phanerozoic continental platform cover sequences (Figure 2). Limited exposure of Archean age rocks requires that boundary zones between Archean age provinces be inferred primarily from

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geophysical data. However, geochemical studies of the Archean age rocks of

Laurentia (e.g., Wooden and Mueller, 1988; Mueller et al., 1988; Frost and

Chamberlain, 1998; Frost, 2000) demonstrate that these early Archean cratons

are distinct in their tectonic evolution and were likely widely distributed prior to

terminal collision. Hence, the inferred geophysical boundaries coincide with

convergent margins along multiple boundaries.

The most significant collisonal event of the "Pan-American System" (Lewry

and Collerson, 1990) is the Trans-Hudson orogeny, which is the terminal

collisonal event between northern and southern Archean elements of Laurentia.

The Trans-Hudson orogen, as popularly defined, extends from central Greenland

across Hudson Bay and from there west-southwest through the exposed

Canadian shield to its type locality in northern Manitoba and Saskatchewan and

is interpreted to continue southward under Phanerozoic cover along the

boundary between the Wyoming and Superior provinces (Lewery and Collerson,

1990; Hoffman, 1990).

Problems with "Trans-Hudson"

Hoffman (1990) stated that the name "Trans-Hudson" orogen (Hoffman,

1981) was intended to identify the Early Proterozoic collision zone between the

Superior Province and the Archean domains of the northwest Churchill Province

(i.e., Hearne-Rae provinces, the Nain Province, and intervening juvenile

terranes) and that the name was an afterthought that lacked precise definition.

The term has been applied to the deformed boundary zone between the

Wyoming and Superior provinces (Dakota segment) and is engrained in the literature of the 1990's (e.g. Redden et al., 1990; Klasner and King, 1990; Nelson et al., 1993; Baird et al., 1996). Multiple lines of evidence suggest that the application of the term "Trans-Hudson" to the Wyoming-Superior collisional zone is inappropriate. The Trans-Hudson orogeny, as popularly defined, is largely buried over the ~2800 km trace of the orogen. The lack of exposure over the trace of the orogen necessitates dependence on geophysical methods to define the orogen and interpret the structural complexity. Other enigmatic structures, such as the Great Falls Tectonic Zone (GFTZ) and the Vulcan Structure (cf., Mueller et al., 2002, 2005) (Figure 2), have traditionally been interpreted to be separate from the Trans-Hudson. Recent work in the GFTZ (e.g. Mueller et al., 2002; 2005) suggests that the traditional interpretation is equivocal. Finally, the age and character of the Trans-Hudson in Canada as compared to the Dakota segment is quite different.

Exposure

Only in the central Canadian shield is the Trans-Hudson well exposed over a broad corridor with strike-length of approximately 500 km, although sizeable areas have been mapped near the eastern shore of Hudson Bay (Thomas, 2001). North of the central Canadian shield, the Trans-Hudson crosses underneath the Paleozoic Hudson Bay basin and then presumably reappears in Greenland and Baffin Island (Mukhopadhyay and Gibb, 1981; Hoffman, 1990; Lewry and Collerson, 1990). However, Hoffman (1987, 1988,

1990) argued for the exclusion of the Greenland and Baffin Island segments with respect to the Trans-Hudson, based primarily on the location of possible sutures and the degree of continuity of juvenile terranes. South of the central Canadian shield, the Dakota segment of the "Trans-Hudson" is buried under Phanerozoic and younger rocks and is only exposed in the ~40 km x 80 km Black Hills uplift (Figures 2 and 3). Rocks exposed in the Dakota segment are also considerably younger than Hudsonian (cf. Redden et al., 1990; Dahl et al., 1998; McCombs et al., 2003; Dahl et al., 2003; Dahl et al., 2005a,b). Precambrian rocks of Hudsonian age are, however, exposed within the GFTZ in the Little Belt Mountains, Montana (cf. Mueller et al., 2002, 2005 and references therein).

Geophysical Interpretation

Extrapolation of lithologic domains in the Trans-Hudson to the Dakota segment was initially developed largely based on a very short seismic reflection profile in southern Saskatchewan adjacent to the exposed part of the orogen (Green et al., 1980, 1985; Klasner and King, 1990; Nelson et al., 1993). Green et al. (1985) extrapolated terranes mapped within the exposed portion of the Trans-Hudson orogen in Canada southward along the deeply buried collisional zone between the Wyoming and Superior provinces based on geophysical interpretation of regional aeromagnetic, gravity, and seismic reflection and refraction data. Using aeromagnetic and gravity data along with limited drill core data, Klasner and King (1986, 1990) further subdivided the buried collisional zone into five lithotectonic terranes that corresponded to the Lewry et al. (1985)

subdivision of the exposed Trans-Hudson in Canada. Klasner and King (1990) also advanced a crustal model for the Dakota segment (Figure 36) based on the idealized orogenic model of Hatcher and Williams (1986). Nelson et al. (1993) presented a summary report of new seismic data collected by the Consortium for Continental Reflection Profiling (COCORP) approximately 700 km south of the exposed Trans-Hudson in Canada. Baird et al. (1996) presented a more detailed analysis of the COCORP data.

The Dakota segment has been ingrained in the literature as "Trans-Hudson" based primarily upon the interpretations of Camfield and Gough (1977) and Klasner and King (1986, 1990; Figure 36). However, based on the COCORP data collected in 1990, Nelson et al. (1993) and Baird et al. (1996) demonstrated that the earlier extrapolations of lithotectonic domains based on correlation with exposed parts of the Trans-Hudson are not appropriate (Figure 38). New Lithoprobe (Canada's national geoscience project) data immediately adjacent to the exposed Trans-Hudson also rebuts the model of Klasner and King (1990) (Nelson et al., 1993; Lucas et al., 1993; White et al., 1994). Both the COCORP data and the Lithoprobe data record structural relations opposite to what was predicted by the existing interpretations of the evolution of the Dakota segment (e.g., Lewry et al., 1990; Klasner and King, 1990).

The new COCORP data (Figure 37) also demonstrates a widely different MOHO signature for the exposed Trans-Hudson versus the Dakota segment (Nelson et al., 1993; Baird et al., 1995; Baird et al., 1996). The exposed Trans-

Hudson shows a sharply defined subhorizontal MOHO. In contrast, the Dakota

segment shows no evidence of this feature. Dipping reflectors in the Dakota

segment are reported to die away at two-way travel-times appropriate for the

upper mantle. This dissimilarity between the Trans-Hudson proper and the

Dakota segment is significant as sharply defined subhorizontal MOHO's are

indicative of collapsed (or collapsing) orogens (Nelson, 1991).

Possibly the least well understood geophysical feature associated with

Laurentian assembly is the North American Central Plains electrical conductivity

anomaly (NACP; Figure 38). Extensive studies have shown that the NACP

extends from northern Canada into the Dakotas (e.g., Alabi et al., 1975; Camfield

and Gough, 1975; Jones et al., 1993, 2005; Garcia and Jones, 2005). Camfield

and Gough (1977) suggested that the NACP marks the Proterozoic collisional

zone from the southern Rockies to northern Canada.   In the Dakotas, the NACP

was interpreted to delineate the eastern boundary of the Wyoming Province

(Dutch, 1983; Klasner and King, 1986). Jones and Savage (1986) relocated the

NACP boundary eastward, where it coincides with the eastern boundary of the

later discovered Dakota block (Nelson, 1993; Jones et al.,1993; Baird et al.,

1996). The cause and tectonic significance of the NACP is still under

investigation (e.g., Jones et al., 2005; Garcia and Jones, 2005; Ferguson et al.,

2005; Evans et al., 2003, 2005). Most workers (e.g., Jones et al., 1997, 2005;

Garcia and Jones, 2005; Ferguson et al., 2005; Evans et al., 2003, 2005)
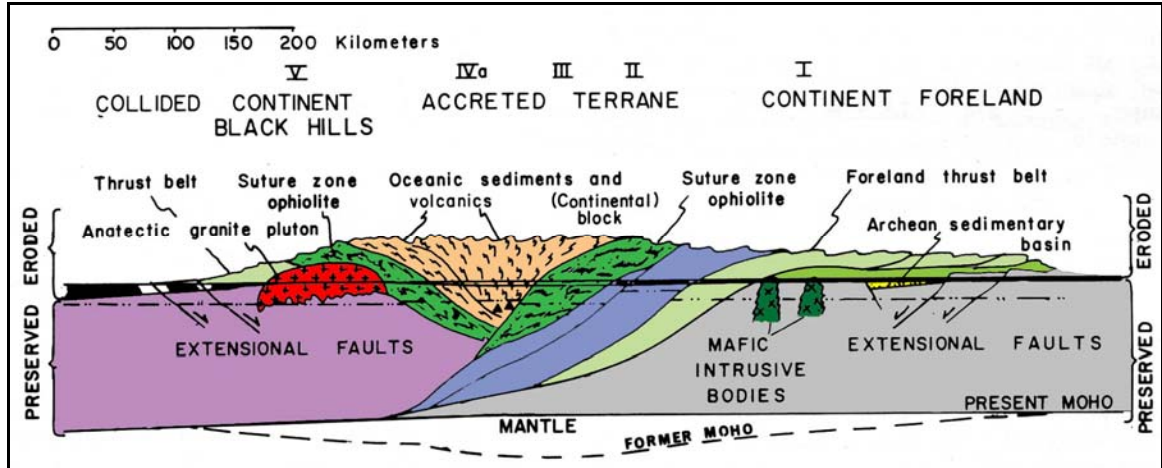
Figure 36 - Tectonic crustal model modified from Klasner and King (Figure 5d, 1990). Purple = Wyoming Province; Gray = Superior craton; Red = Harney Peak type anatectic granite. Light greens= Thrust belts; Medium green = ophiolites; Dark green = Mafic Intrusives; Light tan = Accreted oceanic sediments, volcanics, and continental blocks; Yellow = Archean sedimentary basins.
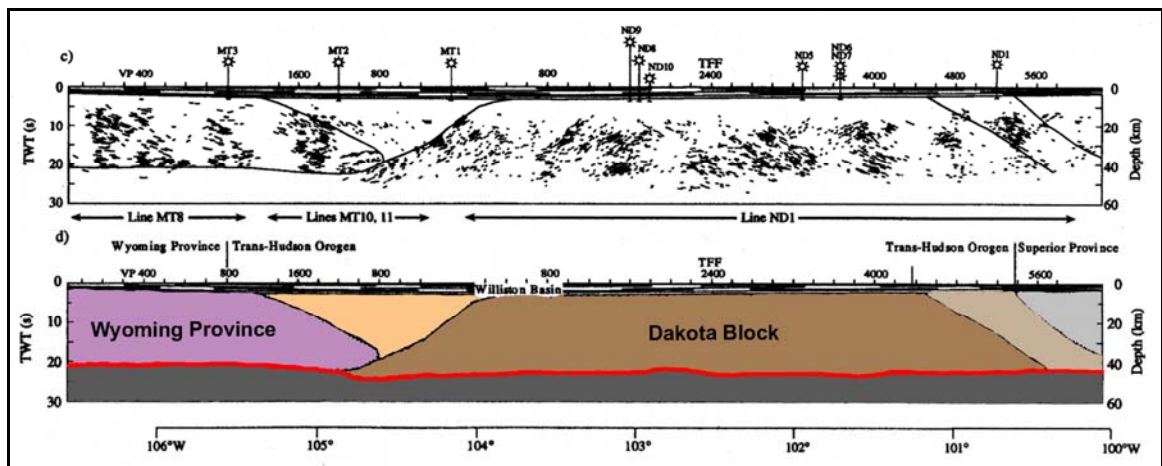
Figure 37 - COCORP seismic transect across the southern Trans-Hudson orogen beneath the Williston Basin. Upper figure is migrated line drawing from data. Lower figure is interpretation of Baird et al. (1996). Red line is the MOHO. Figure modified from Baird et al. (Figure 2, 1996). Purple = Wyoming Province; Dark Brown = Dakota block; Light tan = marginal basin rocks; Taupe = reworked Archean marginal rocks; Grey = Superior craton.
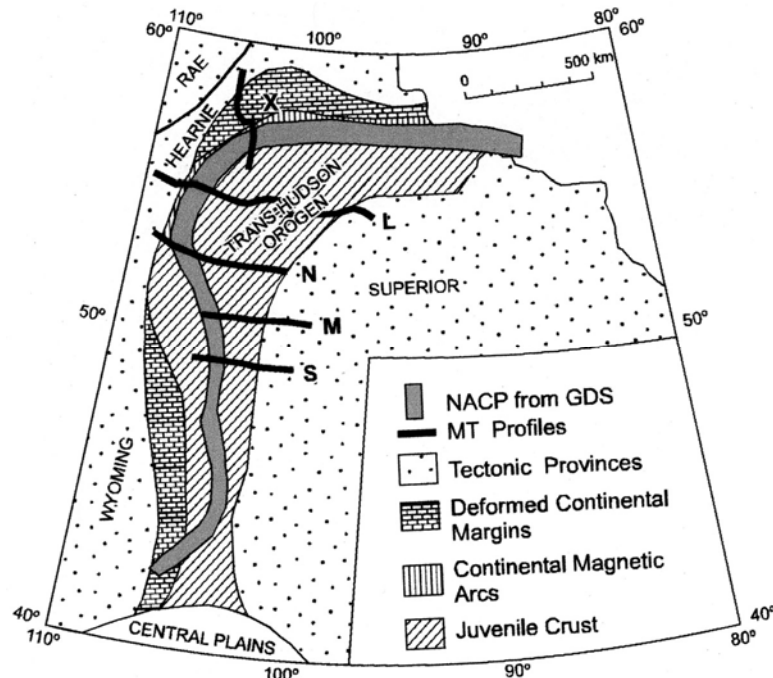
Figure 38 - Location of the NACP conductivity anomaly in Central North America. From Garcia and Jones, 2005.

associate the NACP with sulfide mineralization, not graphite mineralization

(Camfield and Gough, 1977). Geologically, the NACP has been interpreted to be

related to "carbonated and metamorphosed slate rocks" deposited in foreland

basins (Boerner et al., 1996) or sulfide deposits in fold-hinges of volcanic rocks

(Jones et al., 1997, 2005). A characteristic and enigmatic feature associated

with magnetotelluric investigations of the NACP is that it only affects currents

parallel to strike and has little observable effect perpendicular to strike (Jones,

1993). Moreover, magnetotelluric studies of ancient subduction-collision zones

show that some have associated conductivity anomalies while others do not

(Jones et al., 1993). Therefore its tectonic significance in southern Laurentia is

equivocal.

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Age and Character of "Trans-Hudson" Rocks

The southern continuation of the Trans-Hudson orogen is buried underneath Phanerozoic cover sequences (Figure 2). The proximity of the Black Hills uplift to the exposed Trans-Hudson and the trace of the NACP anomaly (Camfield and Gough, 1977) resulted in the early accepted continuation of the Trans- Hudson through the Black Hills. Multiple investigations (e.g. Dahl et al., 1999 a, b; Nabelek et al., 2001; Chamberlain et al., 2002) have since recognized the incongruity of dates associated with terminal collision of the exposed Trans-Hudson (~1900-1830 Ma; Sims and Peterman, 1986; Bickford et al., 1990) with the inferred southern continuation (~1760-1715 Ma; Dahl and Frei, 1998) in the Black Hills. The Trans-Hudson is broadly coeval with the Penokean, Wopmay, and Ketilidian orogens (Hoffman, 1988), thus implying nearly simultaneous orogeny along multiple margins. Continued tectonic convergence resulting in the later "Black Hills" orogeny however, does not necessarily connote equivalence. The recognition of the intervening Dakota block (Baird et al., 1996) undermined the detailed correlation of Klasner and King (1986, 1990) between the Dakota segment and the subprovince delineation of the Trans-Hudson orogen in northern Canada. Moreover, the Great Falls Tectonic Zone, generally considered to be the boundary between the Archean Medicine Hat block (Hearne province) and Wyoming province, yields ages more closely related to the Trans-Hudson proper (1867 +/- 6 Ma [07]Pb/[206]Pb age; Mueller et al., 2002). Mueller et al. (2002) interpreted the Great Falls Tectonic Zone to represent a convergent

margin that developed during the closure of an ocean basin along the northwestern margin of the Wyoming craton at ~1.9 Ga.   This strongly suggests a more definite temporal connection with the Trans-Hudson orogen than that of the Dakota segment.

The Trans-Hudson as exposed in Canada also contains a collage of mainly juvenile, arc-related Early Proterozoic terranes (Baird et al., 1996). These arcs, associated inter-arc sedimentary basins, and older crustal elements were intensely reworked during the Trans-Hudson orogeny (Baird et al., 1996). Geochronological data reveal no consistent age differences between these domains (Lewry et al., 1994). The existence of extensive intervening juvenile terranes in the Dakota segment remains equivocal (e.g. Baird et al., 1996). The lack of juvenile terranes, a primary argument of Hoffman (1988, 1990) to exclude Greenland and Baffin Island segments from the Trans Hudson, taken with the age disparity suggests a different progression for the Dakota segment and Trans-Hudson orogen.

Data for mafic to felsic igneous and metamorphic rocks of the Great Falls Tectonic Zone demonstrate that they were derived from underplated mantle sources and not from older crust (Mueller et al., 2002), again suggesting a stronger connection to the Trans-Hudson orogen than that of the Dakota segment. Mueller et al. (2005) state that the magmatism and metamorphism in the Great Falls Tectonic Zone (~1.86 Ga; Dahl et al., 2000; Mueller et al., 2002) is temporally equivalent to the Trans-Hudson Orogeny. However, Boerner et al., (1998) cited the lack of a collinear magmatic arc and the failure of

electromagnetic studies to detect a plate-edge foreland basin and interpreted the

Great Falls Tectonic Zone as a reactivated intracontinental suture zone rather

than a Proterozoic age suture between the Wyoming and Hearne provinces.

Wyoming Province Orogenies

Multiple workers (e.g., Dahl and Frei, 1998; Dahl et al., 1999 a, b; Nabelek

et al., 2002; Chamberlain et al., 2002) have recognized the diachroneity of

terminal collisions for the exposed Trans-Hudson orogeny and southern Dakota

segment as discussed above. Dahl and Frei (1998) revived the term "Black Hills

orogeny" (Goldich et al., 1966) to distinguish the southern Dakota segment from

the Trans-Hudson. Chamberlain et al., (2002) suggested two separate events:

(1) the 1.78 Ga Black Hills orogeny and (2) the 1.72 Ga Dakotan Orogeny. The

older, ca. 1.78 Black Hills orogeny is coeval with other orogenic events along the

southern (Cheyenne Belt; Chamberlain, 1998) and northwestern margins of the

Wyoming Province (Great Falls Tectonic Zone; Mueller et al., 2005).

This study suggests a two-phase, protracted single event along the

eastern margin of the Wyoming Province that encompasses both the Black Hills

and Dakotan orogenies (cf. Tables 1 and 2). Shackleton and Ries (1984) state

that post-collisional movements are responsible for most observed structures in

orogenic belts. Although there is much validity to that statement, it is

undoubtedly an oversimplification. Many collisional orogens do exhibit multiple

distinct deformational phases caused by a single collisional event (e.g.

Laubscher and Bernoulli, 1982; Duncan, 1984; Ellis 1986; Vannay and Steck, 1995; Pignotta and Benn, 1999). The Black Hills are a prime example of this.

Transpressional Model for the Study Area

Data from this study are difficult to interpret with respect to the traditional "Trans-Hudson" model for the Black Hills. Traditionally, the Proterozoic core of the Black Hills has been described as a series of small epicratonic rift basins (Gosselin et al., 1988). However, this model (c.f. Redden et al., 1990) has been insufficient to explain the complexities of the exposed Precambrian terrane. New and refined age data (e.g., Dahl et al., 2005a,b; McCombs et al., 2003; Dahl et al., 2003; Chamberlain et al., 2002; Dahl et al., 1998) demonstrate that the rocks of the Paleoproterozoic Black Hills underwent a distinctly younger collisional event that is not related to the Trans-Hudson orogen.

Structural patterns observed in the study area and in the east-central and northeastern Proterozoic Black Hills are best explained by an oblique tectonic collision. Orogens must involve some component of oblique convergence as a result of basic plate kinematics and relative plate motion on a spherical surface. Oblique convergence is now considered to be an important part of collisional orogenic systems. I suggest that north-directed movement of the Dakota block resulted in transpression along the east side of the Black Hills. Evidence for transpressional tectonic motion, presented below, is based on:

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1. The presence of the major structural discontinuity that is present in the study area northeast of the Harney Peak Granite that truncates earlier structures.

2. The north-northwest continuation of this structural discontinuity.

3. The ability of transpression to explain lithostratigraphic differences between fault-blocks and the previously recognized "cryptic" folding event across the central and northern Black Hills.

4. The ability of transpression to explain the intrusion, distribution, and metamorphism of the Harney Peak Granite.

5. The paucity of pre-1715 Ma porphyroblasts northeast of the structural discontinuity.

6. The bimodal distribution of $^{40}Ar/^{39}Ar$ dates on either side of the structural discontinuity.

7. The overall pattern of faulting in the east-central and northeastern Black Hills.

Structural Discontinuity

As discussed above, a major structural discontinuity exists along the Keystone Fault over much of the study area. Along the west-central portion of the study area, the structural discontinuity is marked by the Empire Mine Fault as displacement is transferred from the Keystone Fault to the Empire Mine Fault as they merge along a single fault-segment in the Hill City quadrangle (Ratte and Wayland, 1969) and then diverge farther to the northwest (Figure 27). The structural discontinuity is then marked by the trace of the Empire Mine Fault to the northwest. The Empire Mine Fault continues northwest through the Hill City quadrangle (Ratte and Wayland, 1969) and the Silver City quadrangle (Redden et al., 2005). In the Silver City quadrangle, the Empire Mine Fault apparently

bifurcates into east and west branches (Redden et al., 2005). The structural discontinuity is presumably carried along the east branch of the Empire Mine Fault as the west branch appears to tip out into a large fold nose (cf., Redden et al., 2005), although displacement may be transferred to the Silver City Fault. The Silver City Fault is consistent with the biotite metamorphic isograd along most of its length (cf. Figure 6; Nabelek et al., *in press*) implying a metamorphic break across the fault zone.

Evidence noted above demonstrates that this discontinuity is a sinistral strike-slip fault zone, which predates the Harney Peak Granite intrusion. The discontinuity continues northwest through the Hill City and Silver City quadrangles where it truncates all earlier structures to the southwest (cf. Figure 7; Dewitt et al., 1989; Ratte and Wayland, 1969; Redden et al., 2005). The overall pattern of mapped faults northeast of the discontinuity (Figure 39; cf. Figure 7) implies a dominantly strike-slip component to faulting; hence, the area northeast of the mapped discontinuity could represent various "tectonic slivers" moved unknown distances along the margin of the Archean Wyoming craton (Figure 39; cf. Figure 27). The idea of the fault-bounded blocks representing "tectonic slivers" is supported by the lack of determinate stratigraphic relations between fault-bounded blocks within the Mount Rushmore quadrangle. Dissimilar structural histories for fault-blocks A, B, and C as compared to fault-blocks D – I and similar but unique structural histories for fault-blocks D – I also support this idea (Figures 5 and 15 – 20).
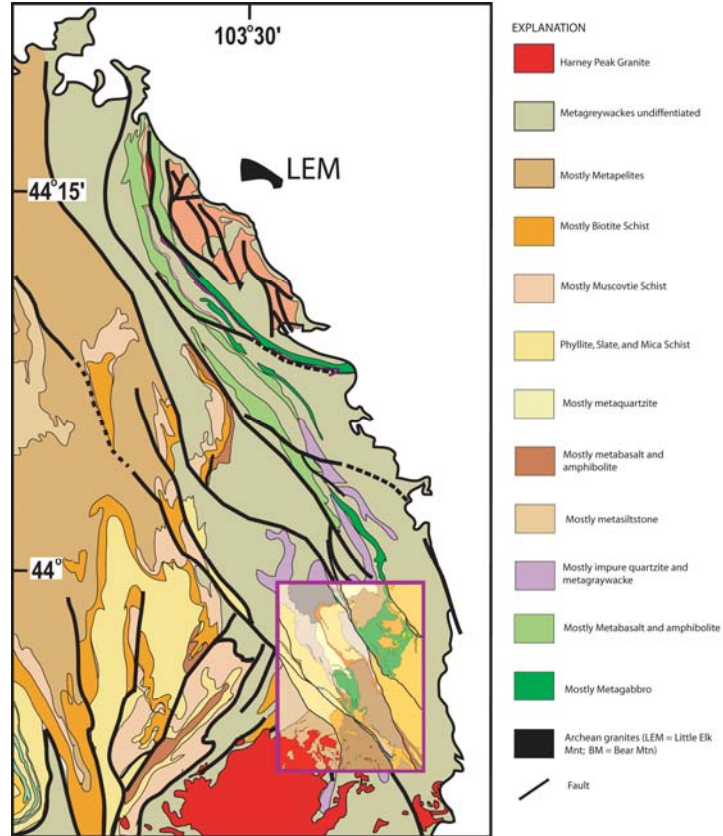
Figure 39 - Generalized geologic map of the northeastern Black Hills. Purple box outlines the Mt. Rushmore quadrangle and contains a scaled inset of detailed mapping completed during this study. Compare with Figures 7 and 27. Detailed mapping is needed to delineate the structural detail of the eastern Black Hills and elaborate on the proposed transpressional model.

Emplacement of the Harney Peak Granite

The mechanisms of ascent and emplacement of granitic magma are still

an area of intense investigation and considerable debate (e.g., Paterson et al.,

1989; Simpson, 1999; Paterson and Schmidt, 1999; Brown and Solar, 1998

a,1998b). Granitic magmas are the principal agents of heat and mass transfer

through the Earth's crust (Yoshinobu et al., 1998 and references therein) and

have been extensively used to constrain the time of deformational events (e.g., Miller et al., 1999).

Understanding the timing and emplacement of plutons is critical to interpretations of the age and significance of structures and metamorphism in orogenic terranes. The spatial and temporal association of syntectonic granites and regional tectonic structures has been demonstrated for many orogenic belts (e.g., Weinberg, 1996; Brown and Solar, 1999), yet the mechanisms responsible for ascent and emplacement of plutons are not well constrained. Ascent of magmas is generally described by one of two end-member models: (1) diapirism or (2) diking. Each model has its own inconsistencies in its ability to successfully emplace substantial amounts of new material into the crust. The most basic problem for both models is how room is made for the ascending magma bodies.

In convergent settings, it is clear that that there must exist structural controls on the ascent and emplacement of plutons. Hence, it follows that there must be a relationship between deformational and thermal processes. Simpson (1999) recognized that a valid argument could be made for the uniqueness of each pluton with respect to its source, transport, and emplacement characteristics. Brown and Solar (1998a, 1998b, 1999) suggested that in transpressive orogens ascent of magma is controlled by tectonic structures. Space is made both by the magma itself (ballooning, stoping, viscous flow of the wall rocks) and by creation of dilational space (e.g., Hutton, 1988; Glasner, 1991). Collins and Sawyer (1996) suggested a pervasive flow model for melt migration through partially molten crust. In this model, a feedback relationship

exists between deformation and melt generation. Melt pressure increase leads to melt-enhanced embrittlement of the crust (Davidson et al., 1994). Shear zones develop in response to rheologic heterogeneities in the crust that can be enhanced by the presence of melt. The melt then migrates through the crust along the shear zone extending the zone of pervasive flow (Brown and Solar, 1998a). Flow is driven by pressure gradients generated by tectonic stresses over short distances and by magma buoyancy over longer distances (Rutter, 1997). Whatever the mechanisms for ascent of felsic magma, space must still be made for their emplacement. Magmas clearly find or open space for themselves.

The main body of the Harney Peak Granite and its satellite plutons occupy an area of roughly 100 km^2 in the south-central Black Hills (Figure 27). The mechanisms of emplacement of the main Harney Peak Granite has been inferred by analogy from the study of one of its smaller satellites (~1 km^2), the Calamity Peak pluton (Duke et al., 1988). The model suggests that the Harney Peak Granite consists of multiple pulses of genetically related magma that were initially disconcordant sills fed by concordant feeder dikes. Each successive pulse was injected forcefully along the upper contact between pre-existing granite layers and the country rock. Continued growth by forceful injection resulted in ballooning of the granite and upward and outward growth of the granite and produced an overall dome-shaped structure of the Harney Peak Granite.

I suggest that sinistral transpression along northwest directed strike-slip faults (i.e. the structural discontinuity along the Keystone and Empire Mine faults) would result in opening dilitational space that resulted in a low pressure gradient

allowing for the emplacement of magma. Nabelek et al. (*in press*) argue that no

doming actually took place during the emplacement of the Harney Peak Granite

and that the fault-block containing the granite was uplifted along the Empire

Mine-Keystone faults on the north and the Hill City Fault along the west. They

cited the strong difference in foliation outside the Harney Peak block (Hill et al.,

2004; Ratte and Wayland, 1969) and metamorphic overprint of the Harney Peak

Granite across the structural discontinuity, along with the presence of late

andalusite as evidence of uplift. Movement along faults in the study area during

or after the emplacement of the Harney Peak Granite is demonstrated by

precipitation of graphite along fault zones (Nabelek et al., in press), prevalence of

secondary fluid inclusions within pegmatites that occur near faults (Sirbescu and

Nabelek, 2003), and overgrowth of M_2 porphyroblasts in fault-related zones

(Figure 26).

If the overall motion along the Empire Mine-Keystone fault system was left

lateral, then a left-step over or releasing bend would have opened dilatational

space along a negative flower structure during transpression (Figures 40 and

41). The emplacement of the Harney Peak Granite would have been facilitated

by opening of dilitational space by northwest-directed sinistral transpression.

Generation of melt would have been accelerated by the release of confining

pressure and because feedback relationships exist between deformation and

melt generation (Brown and Solar, 1998a). Generation, segregation, and

emplacement of the granitic melt would have important affects on the thermal

and rheological behavior of the crust. The melt would have migrated through the

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crust along an inferred listric shear zone (Nabelek et al., 2001) extending the

zone of pervasive flow (Brown and Solar, 1998a). Flow is driven by pressure

gradients generated by tectonic stresses over short distances and
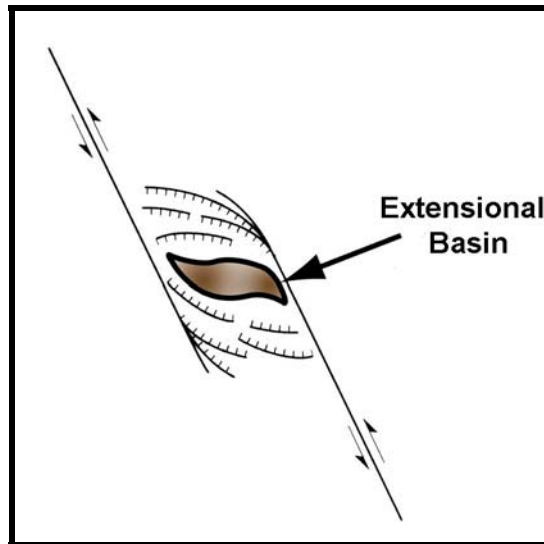
Figure 40 - Diagram showing map view of mechanics of a releasing bend stepover along a sinistral strike-slip fault. Extension and normal faulting occur at high angles to the bounding strike-slip faults and are shown as hatched lines. Modified from Van der Pluijm and Marshak (2004).

by magma buoyancy over longer distances (Rutter, 1997). If deformation and

melt generation are coeval, the introduction of melt into the shear zone will

effectively weaken the crust and locally concentrate strain (Solar, 2006).

The presence of melt within the Harney Peak block would have made it

more buoyant than surrounding blocks (Nabelek et al., *in press*), resulting in uplift

that may have also been facilitated by inversion of the negative flower structure

during progressively more east-west directed compression as shown in Figures

15 - 20. This scenario is supported, in part, by the fact that the Harney Peak

Granite is spatially associated with the structural lowest (and presumably oldest)

Paleoproterozoic rocks of the younger sedimentary succession in the Black
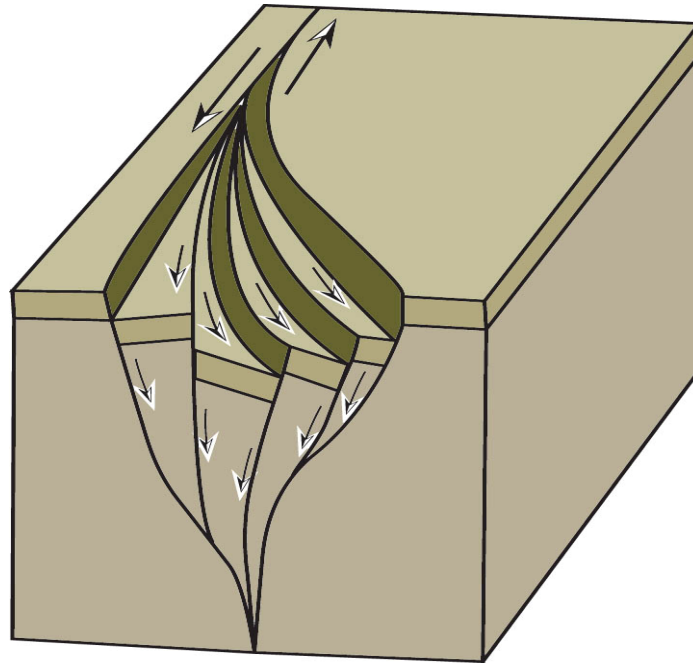
Figure 41 - Block diagram of a negative flower structure. These structures may form from transtensile zones associated with releasing bends in an overall transpressional regime. Modified from Van der Pluijm and Marshak (2004).

Hills (Holm et al., 1997). The recumbent folds (F_1/F_2) recognized in this study

and elsewhere within the Harney Peak block would then be preserved D_{2a}

structures and as a result, F_{2a} folds. These folds then record a weak S_{2a} fabric.

Transposition of these early D_{2a} features occurred outside the Harney Peak

block. Within the Harney Peak block, strain was concentrated by reaction-

enhanced ductility and melting, effectively partitioning the strain into the melt.

The lack of structural overprint by the Harney Peak Granite in adjacent fault-blocks, even though there is a strong metamorphic overprint (Nabelek et al., *in press*), may be explained by strain partitioning in the melt in the Harney Peak block such that little strain was transmitted to the country rocks of adjacent fault-blocks.

M_1 Porphyroblasts and $^{40}Ar/^{39}Ar$ Data

One of the original goals of this study was to relate porphyroblast growth to tectonic fabrics in order to form a basis for dating deformation fabrics. No M_1 porphyroblasts were recognized in the study area, although spotted schists in fault-block B may preserve vestiges of M_1 porphyroblasts (Figure 11b). Nabelek et al. (*in press*) suggested that near the Harney Peak Granite M_1 garnets were wholly replaced by M_2 garnets in response to elevated temperatures and fluid flow. However, remnant M_1 porphyroblasts are preserved to the west of the defined structural break recognized in this study and in places affected by high-grade M_2 metamorphism. Moreover, porphyroblasts related to the thermal overprint of the Harney Peak Granite are ubiquitous in the study area indicating that the rocks (on the east side of the structural break) had the correct chemistry to form early M_1 porphyroblasts, yet no M_1 porphyroblasts were found. Two possibilities exist to explain this delimma: (1) the rocks of the study area initially lacked the correct chemistry to form early porphyroblasts and metasomatic reactions related to the Harney Peak Granite intrusion sufficiently altered the chemistry of the rocks allowing M_2 porphyroblasts to form; or (2) the rocks east of

the structural break initially had the correct chemistry to form early porphyroblasts but were not subjected to the same P-T conditions as rocks that preserve M_1 porphyroblasts west of the structural discontinuity. Although evidence is inconclusive, I believe that the lack of M_1 porphyroblasts east of the structural break is related to translation of the fault-bounded blocks as tectonic slices along the margin of the Wyoming Province.

Available $^{40}Ar/^{39}Ar$ data (Dahl et al., 1999a) also show a remarkable trend when one considers the structural discontinuity. The data show a bimodal age distribution, with one group, SW of the discontinuity, having an average age of ~1735 Ma and a second group, NW of the discontinuity having an average age of ~1350 Ma (Table 4). Dahl et al. (1999a) stated that the cause of the bimodal ages of mica suites was uncertain but suggested that resetting by Tertiary intrusions was likely. When these data are considered with respect to the structural discontinuity defined during this study, all older dates are from samples west of the structural break and all younger dates are from samples east of the discontinuity. $^{40}Ar/^{39}Ar$ data from Holm et al. (1997) also demonstrate that rocks west of the structural break yield older dates. Data presented for muscovite and biotite, (Dahl et al., 1999a) show broad flat plateaus, which are not consistent with thermal resetting. Moreover, micas from the Nemo area (Figure 3) show a broad range of dates (> 150 m.y.; Dahl et al., 1999a). This area is intensely faulted and, although not conclusive, these age data demonstrate the need for more investigation of the fault-bounded blocks as potentially separate tectonic blocks with unique structural histories.

^{40}Ar/^{39}Ar data for hornblende (Dahl et al., 1999 a, b) show a classic "stair-case" pattern of increasing plateau ages. Thus ages determined by Dahl et al. (1999 a, b) for hornblende are minimum estimates for the ages. All hornblende data were collected west of the structural break leaving no room for comparison of the same type data from the east-side of the structural break. Because no hornblende data east of the structural break are currently available for comparison, the overall pattern may indicate a normal cooling pattern across unrelated terranes. However, hornblende data are highly concordant with mica data from the west-side of the structural break, again supporting the disparity in age relationships across the structural discontinuity.

SW of the Structural Discontinuity			NE of the Structural Discontinuity		
Sample	Mineral	Age (Ma)	Sample	Mineral	Age (Ma)
BH-3	Hornblende	1691 ± 5	LEG-1	Biotite	1341 ± 4
CM-2242	Hornblende	1787 ± 8	LEG-8	Biotite	1307 ± 7
T93-6	Hornblende	1736 ± 13	LEG-10	Biotite	1396 ± 5
T93-6	Hornblende	1714 ± 10	LEG-15	Biotite	1286 ± 7
T93-6	Hornblende	1742 ± 6	LEG-25	Biotite	1457 ± 7
T93-6	Hornblende	1742 ± 5	NM-1	Muscovite	1361 ± 13
*HM-1007***	Muscovite	1221 ± 9	NM-3	Biotite	1308 ± 8
*HM-32***	Biotite	1304 ± 4			

Table 4 - Summary of ^{40}Ar/^{39}Ar results from the northern Black Hills, Dahl et al. (1999a). **Italicized data are from gold-bearing quartz veins of the Homestake Mine, which lies along the projection of the structural discontinuity.

Overall Structural Pattern and "Cross Folds"

The overall structural pattern of faults east of the defined structural

boundary also strongly suggests strike-slip movement along the traces of

mapped faults (Figure 39). A lack of detailed mapping to the north of the Mount

Rushmore quadrangle limits this discussion to overall trends. Nevertheless, the

pattern is that of a series of anastamosing strike-slip faults and subsidiary faults.

Interpretation is complicated by the heterogeneity of the crust and preexisting

planar weaknesses (e.g. joints, old faults, foliations) that cause stress

concentrations and local changes in stress trajectories (Van der Pluijm and

Marshak, 2004). Gross lithologies are depicted in Figure 39, which was adapted

from the 1:250,000-scale map of the Black Hills (Dewitt et al., 1989). Although

some offset is indicated by the distribution of the rock types, there is no way of

knowing exactly how far any of these blocks may have been translated during

transpression from current evidence, nor have I considered any form of rigid

block rotation. In addition, we cannot assume that the present day erosional

surface is parallel to the σ_1-σ_3 plane of the strike-slip faults.

Transpression can also explain previously recognized but enigmatic

structural relationships in the Proterozoic core of the Black Hills, for example the

presence of "cross-folds" (cf. Redden et al., 1990; Noble et al., 1949), the

differences in lithostratigraphy among fault-bounded blocks in the east-central

Black Hills, and the chemical and structural dissimilarities that exist between the

two Archean granite exposures (Little Elk Mountain and Bear Mountain granites).

The F_3 cross-folds, discussed previously, can be explained as *en echelon* arrays

of folds typically associated with continental strike-slip faults. It would be advantageous to find and better describe these cross-folds and their relationship to fault zones throughout the east-central Black Hills. This study presents evidence for dissimilar lithostratiphic relationships within the fault-blocks of the Mount Rushmore quadrangle, which may be explained by transpression of these fault-blocks along the eastern margin of the Wyoming Province. Another example of the discontinuity of lithostratigraphy is the fact that the older Paleoproterozoic succession is restricted to the Nemo area. Moreover, the mafic rocks of the Little Elk terrane are calc-alkaline, suggesting an arc-related genesis, while the mafic rocks of the Mount Rushmore quadrangle and elsewhere in the Black Hills have N-MORB affinities (Nabelek, unpublished data). This strongly implies juxtaposition of terranes by transpression in the east-central Black Hills. Much debate has occurred as to the dissimilarities (I-type versus S-type; REEs etc.) of the Little Elk and Bear Mountain Archean exposures, which is easily explained by being genetically unrelated and juxtaposed by transpression.

Application of the Transpressional Model to the Black Hills

A transpressional model for the Black Hills is a very attractive tectonic paradigm as oblique convergence is now generally considered part of collisional orogens. Previous tectonic models have called upon multiple sialic rifts in the Black Hills to explain the lithologic differences juxtaposed over relatively small distances (cf. Redden et al., 1990). Transpression can also explain the differences in lithostratigraphy between fault-blocks. Previous workers have also

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called upon cryptic tectonic events to explain various structures in the Black Hills, for example a regional F_1 folding event that produced no penetrative fabric or cryptic tectonism to explain "cross-folds" (cf. Redden et al., 1990).

The transpressional model simplifies the overall tectonic setting with respect to the number of events needed to produce the recognized deformation. With a transpressional model, early north-directed folds (D_{2a}) and later north-west directed (D_{2b}) folds could be products of the same transpressional event as the convergence direction changes. The emplacement of the Harney Peak Granite and the lack of agreement between the metamorphic and structural overprints related to emplacement can be explained with a transpressional model. The overall mechanism for the emplacement of the Harney Peak Granite can be explained in the context of available thermo-barometric studies (cf. Nabelek et al., *in press*) using a north-directed transpressional model. The late regional event resulting in a spaced cleavage over much of the southern Black Hills may also be related to final collision.

Transpressional Model

Earlier studies of the Black Hills called for as many as five separate deformation events and rather complex explanations for the tectonic history of the Black Hills and, by extrapolation, for southern Laurentia. This study considers three deformational events, discussed below, as a basis for formulating a transpressional tectonic model for the Black Hills and its relationship to the assembly of southern Laurentia.

Deformation in the Black Hills was produced by the collision of the Wyoming Province and the Dakota block (e.g. Dahl et al., 1999 a, b; Chamberlain et al., 2002). The deformation was partitioned into two events: (1) the D_{2a} event (correlative with the Black Hills orogeny), and (2) the D_{2b} event (correlative with the Dakotan orogeny). Figure 42 illustrates the possible configuration of the Wyoming Province and Dakota block from 1780 – 1720 Ma. Northwest directed translation of the Dakota block was a result of the 1780-1740 Ma Medicine Bow orogeny (Chamberlain, 1998). Oblique convergence ~1760 – 1740 Ma resulted in NW-SE compression (D_{2a}) that formed the major early D_{2a} folds (F_1 nappe structures as reported in earlier studies: e.g., Redden et al., 1990; Dahl et al., 1999 a, b). It is possible that the shape of the intervening margins of the Wyoming Province and Dakota block played a substantial role during the early D_{2a} deformation, as the interaction of recesses and salients produced complex interactions during their convergence. Collision between the Wyoming Province and the Dakota block became progressively more west-directed as shown by Figures 15 – 20 and likely coincides with the ~1755 – 1710 Ma ages of garnets from the Bear Mountain area (Dahl and Frei, 1998). Continued northwest translation of the Dakota block (relative to the Wyoming province as shown in Figure 42), resulted in the third period of deformation that produced progressively more strike-slip movement along the eastern edge of the Black Hills. Dilational space was opened up along the defined structural boundary allowing for the emplacement of the Harney Peak Granite and related deformation. Pieces of the intervening deformational zone between the

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Wyoming Province and the Dakota block were then moved northwestward as the

Dakota block slipped past the eastern edge of the Wyoming Province.

Translation of these tectonic slivers resulted in F_3 cross-folds that locally

overprint the dominant F_2 folds. The late spaced cleavage recognized in this

study is interpreted to be a result of the subsequent Central Plains orogeny.
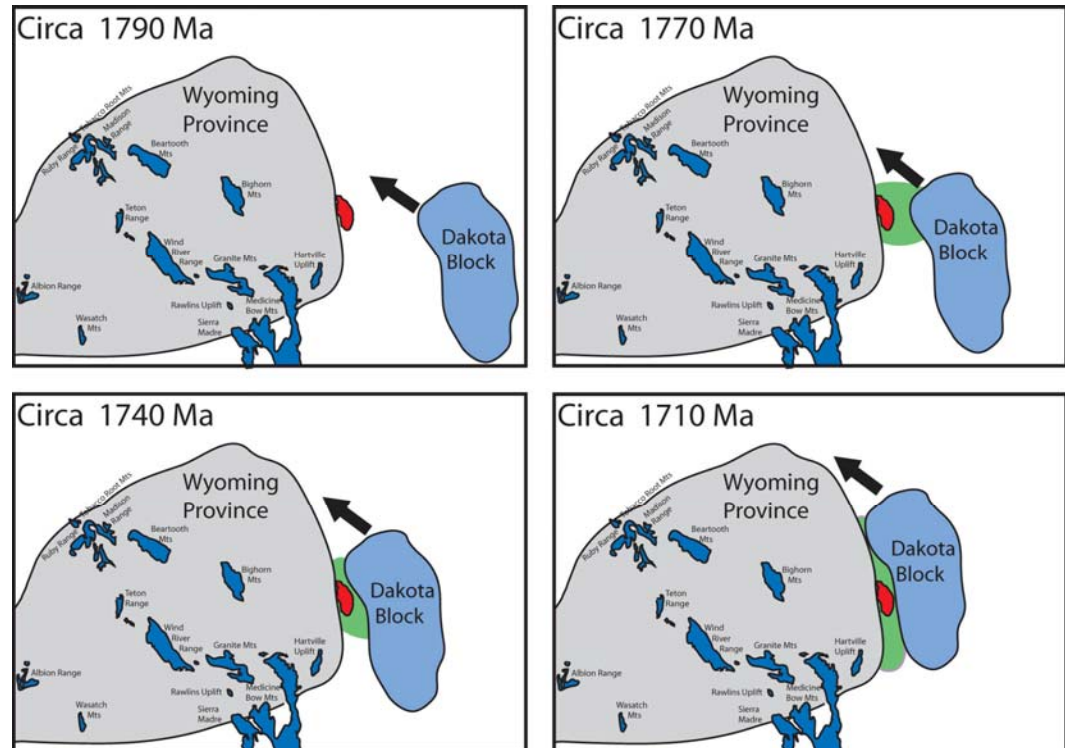
Figure 42 - Possible configuration of the Wyoming Province and Dakota block during 1760-1715 Ma collision. Red area denotes present day Black Hills uplift, Blue areas are other Laramide basement uplifts that expose Precambrian cores. Green area denoted the region affected by deformation.

Extrapolation to the Tectonics of the Wyoming Province

Mueller et al. (2005) presented a very good model for the assembly of

southern Laurentia invoking simultaneous SW-NE convergence of the Hearne,

Medicine Hat, and Wyoming provinces. However, they could not reconcile the

younger orogenic events that occurred along the eastern margin of the Wyoming

province (Black Hills and Dakota orogens). Nor did they take into account the

recently recognized correlation of the Dakota block with the the Sask craton (e.g.,

Bickford et al., 2005) which underlies the Glennie and Flinn Flon Domains of the

Trans-Hudson.

One of the major shortcomings of the Mueller et al. (2005) model is that it

requires the Black Hills to be part of the 1.97 – 1.85 Ga Trans-Hudson orogeny

based on superseded dates for tectonothermal events in the Black Hills as

reported by Gosselin et al. (1988) and Redden et al. (1990). There is no

evidence that the Black Hills underwent collisional tectonism prior to 1790 Ma

(e.g., Dahl et al., 1998; Dahl et al., 1999 a, b; Chamberlain et al., 2002;

McCombs et al., 2003). The Mueller et al. (2005) model, however, improves

upon the model of Dahl et al. (1999 a, b) which required two orthogonal

subduction zones, one dipping westward underneath the Wyoming Province and

one dipping northward underneath the Wyoming and Superior Provinces.

The assembly of southern Laurentia involved collisions between the

Wyoming Province, the Superior craton, the Medicine Hat block, the Sask craton,

and the Hearne-Rae Province that occurred prior to the circa 1600 Ma Central

Plains orogeny.   Collectively, the number of terranes and the temporal overlap of

their juxtapositions present many geodynamic problems. Figure 43, which is an

attempt to address some of the major problems, illustrates a possible

configuration for major Archean and Paleoproterozoic crustal blocks incorporated

into southern Laurentia between 1.9 and 1.7 Ga.

I suggest that convergence of the Medicine Hat block , Hearne province, and Wyoming province occurred much as depicted by Mueller et al. (2005). However, convergence along the subduction zone shown in Figure 43 was not a steady state. I propose that subduction between the Superior and Hearne-Rae provinces was fast, while the western portions of the zone it was slower
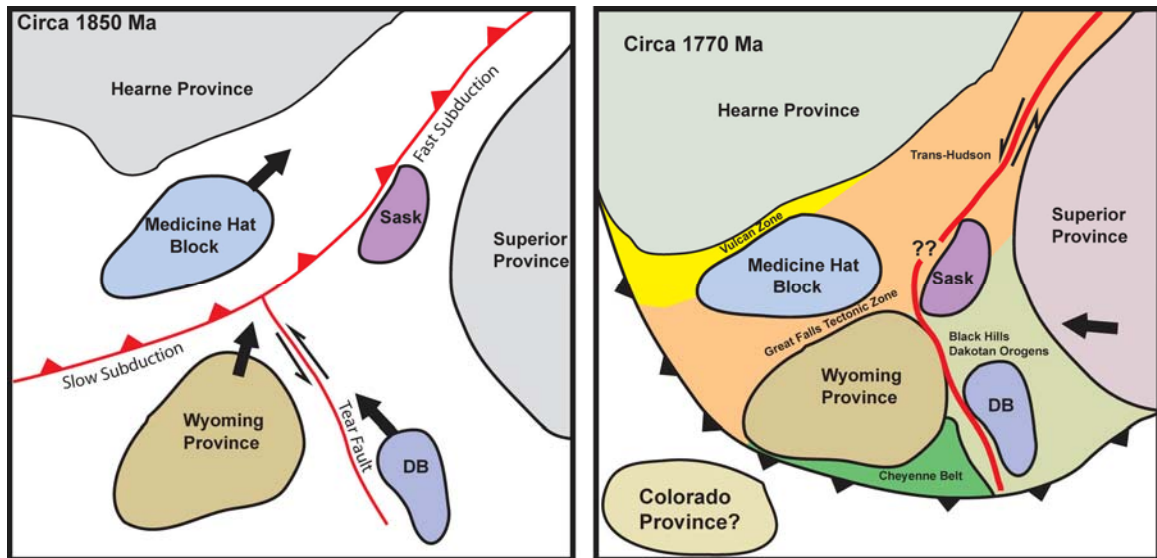
Figure 43 - Depiction of potential configuration of major cratonic blocks of now part of southern Laurentia. Black arrows show direction of movement. Subduction zone polarity shown by teeth that point in direction of subduction. DB = Dakota Block.

(i.e. Medicine Hat-Hearne, Wyoming-Medicine Hat). This resulted in a large-scale tear fault orthogonal to the north-directed subduction as shown in Figure 43. The Trans-Hudson proper was a result of fast, north-dipping subduction that juxtaposed the Hearne-Rae and Superior cratons and accreted intervening terranes. This fast subduction led to the Sask craton being overthrust by the arc-related rocks of the Glennie and Flinn-Flon domains (Chiarenzelli, 2002) as first suggested by Lewery et al. (1990). In the west, collision between the Medicine Hat and Hearne provinces resulted in the Vulcan tectonic zone, but

timing of this collision remains uncertain. Subsequent collision between the Medicine Hat block and the Wyoming Province resulted in the Great Falls Tectonic Zone, which is at least temporally equivalent to the Trans-Hudson. During this collision, northwest directed translation of the faster moving eastern side of the subduction zone brought the Dakota block into the intervening ocean between the Wyoming and Superior Provinces. By ~1820 – 1775 Ma, the north-directed subduction that sutured the Hearne and Superior provinces had become a left-lateral strike-slip boundary (Annesley et al., 2005; White et al., 1999; Lithoprobe Project, http://www.litho.ucalgary.ca/atlas/thot/thot_blurb.html). This left lateral strike-slip led to the terminal collision between the Wyoming and Superior provinces during the Black Hills and Dakotan orogenies.

CONCLUSIONS

1. **Three deformational events are recognized in the Mt. Rushmore quadrangle.** Table 3 summarizes these events and retains the numbering system of previous studies to avoid unnecessary confusion. The earliest event incorporates both the D_1 and D_2 events of previous studies. Previous studies ascribed the D_1 event to a nebulous north-directed collision and the D_2 event to the terminal collision between the Wyoming and Superior Archean provinces. I have chosen to call the earliest event recognized in the study area D_2 and separate it into D_{2a} and D_{2b} subevents. I do so, knowing that it is likely the earliest event that

affected all the Paleoproterozoic rocks in the Black Hills, but have chosen

to keep the D_2 moniker to denote that both subevents are related to the

Wyoming-Superior collision. An oblique collision of the intervening Dakota

block during terminal Wyoming-Dakota block-Superior collision resulted in

portioning the D_2 event into the D_{2a} and D_{2b} subevents. The D_{2a} subevent

formed the earliest folds and faults recognized in the Black Hills and

convergence was more north directed and resulted in early north directed

compression. During oblique collision, the overall convergence became

more northwest directed transpression, resulting in the strong overprint by

D_{2b} folding and fabrics as the Dakota block slipped past the eastern

Wyoming margin. The D_4 event is the second event to affect the

Paleoproterozoic rocks of the study area and is related to the

emplacement of the Harney Peak Granite. Major deformation associated

with the D_4 event in the study area is restricted to fault-block A. The D_5

event affects the southern half of the study area and is likely a result of

far-field stresses related to the Central Plains orogen.

2. **The study area contains nine fault bounded blocks with separate**

   structural histories. The differences in structural patterns, deformation,

   and metamorphism may be explained by a transpression model.

3. **A major structural discontinuity exists along the Keystone and**

   Empire Mine Faults in the Black Hills, South Dakota. Evidence from

detailed mapping in the Mount Rushmore quadrangle demonstrates that this discontinuity is a sinistral strike-slip fault zone. This discontinuity continues northwest through the Hill City and Silver City quadrangles where it truncates all earlier structures to the southwest. The overall pattern of mapped faults north east of the discontinuity implies a sinistral transpressional event; hence, the area northeast of the mapped discontinuity represent various "tectonic slivers" moved unknown distances along the margin of the Archean Wyoming craton.

4. **Emplacement of the Harney Peak Granite occurred during the waning stages of D_{2b} as dilational space was created in a releasing bend during north directed transpression.** Uplift of the fault-bounded block containing the Harney Peak Granite is likely a result of differential buoyancy related to the emplacement of the melt (Nabelek et al., *in press*) coupled with late compression of the releasing bend reactivating the faults in high-angle reverse motion.

5. **Movement along strike-slip faults continued after the emplacement of the Harney Peak Granite.** Mapped faults within the study area are characterized by brittle deformation. Evidence for post-intrusion movement include: (1) abundance of graphite along the major fault zones (Nabelek et al., in press); (2) intense metamorphism by the Harney Peak Granite and presence of late andalusite recording polybaric uplift of the

Harney Peak block coupled with lack of intense deformation outside the

Harney Peak block; and (3) overgrowth of Harney Peak related

porphyroblasts in and near strike-slip faults mapped during this study.

Furthermore, faults mapped during this study truncate structures

interpreted to be directly related to the Harney Peak intrusion and

therefore must be somewhat younger in age. It is postulated that the

overall sinistral transpression is related to the collision of the Cheyenne

Belt from the south prior to the terminal east-west collision of the Wyoming

and Superior cratons. Similar timing of collisional events in the Laramie

Range and Hartville Uplift in Wyoming supports this hypothesis.

6. **The structural pattern observed in the study area, lack of correlative**
   stratigraphy between fault-bounded blocks in the study, and overall
   structure of the east-central Black Hills may be best explained by an
   oblique convergence model.

7. **The Dakota segment represents a younger orogenic event related to**
   the assembly of southern Laurentia. The deformation recorded in the
   Paleoproterozoic rocks of the Laramide Black Hills uplift is not related to
   the Trans-Hudson orogen. The age of deformational events, paucity of
   intervening juvenile terranes, and presence of the Dakota block preclude
   the southern continuation of the Trans-Hudson orogen.

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APPENDIX A – Lithostratigraphic Units

The following is a list of mappable units used during this study and corresponds to the units on Plate I. This list is not a stratigraphy and implies no stratigraphic or age relationships beyond the fact that the Harney Peak Granite is the youngest rock in the study area.

Lithostraphic Units

X_{HPG} - Harney Peak Granite and related pegmatites. Fine grained to pegmatitic, S-type granite. Typically layered parallel or subparallel to dominant foliation. Dominant minerals include oligoclase, microcline, perthite, quartz, muscovite, biotite, and tourmaline. Mineralogy may vary with location, especially with respect to the pegmatites.

X_{qms} – Quartz-mica schists. May contain minor amounts of staurolite and/or garnet with sillimanite prevalent around the contact with the Harney Peak Granite. Dominant minerals include quartz and biotite with lesser amounts of muscovite, opaques in various amounts. Dominant biotite schists interlayered with subordinate metagreywackes. May contain layers of quartzite.

X_{qqm} – Dominantly interlayered quartz schists, quartz-mica schists, phyllites, and mica schists. Thin bedded. Locally shows good primary bedding features. Layers may have relict "spots" of unknown porphyroblasts crossing beds at an angle and defining the axial-plane of larger scale folds.

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X$_{gs}$ – Quartz-biotite-garnet schists, graphitic in part, interlayered with quartz-mica-garnet-staurolite schists with quartz pebbles (matrix supported metaconglomerate)

X$_{sgw}$ – Interlayered quartz-mica schists and metagreywacke, with subordinate graphitic schists, slates, and phyllites. Similar to unit X$_{gs}$ but with thicker-bedded metagreywackes prominent with lesser banded quartzite. No porphyroblasts.

X$_{gw}$ – Medium to thick bedded metagreywacke and quartzite; locally interlayered with quartz-schists and minor phyllites which are common in the northwest part of the quadrangle. Thick bedded quartzose rocks in the northeast part of the quadrangle may have black, glassy beds of graphitic quartzite. Porphyroblasts of garnet and/or staurolite common in more pelitic layers.

X$_{ss}$ – Staurolite-quartz-mica schist and biotite-staurolite-garnet schists with very large staurolite porphyroblasts. Distinctive unit.

X$_{qgw}$ – Mainly interlayered quartz-schist, quartz-mica schists $\pm$ garnet and/or staurolite with interlayered metasiltstones and minor phyllites and slates. Layers of greywacke are locally common. Similar to unit X$_{gw}$ but with much less metagreywacke and quartzose rocks.

X$_{s}$ – Grey to black slates and "spotted" slates and schists with lenses of metasilttone.

X$_{tgw}$ – Interlayered greywacke and slates, mica-garnet schists, and minor quartzite. Similar to units X$_{gw}$ and X$_{qgw}$ but with more schistose rocks having garnet porphyroblasts.

X$_{qs}$ – quartz schists with minor quartz-biotite schists. Dominantly clean quartz-schists with lenses of more pelitic mica schist. Porphyroblasts include staurolite and garnet in the southeast of the quadrangle.

X$_{qps}$ – Quartz phyllite and phyllonitic quartz-schist. Lower grade equivalent of unit X$_{qs}$.

X$_{bs}$ – Biotite schist ± garnet.

X$_{amg}$ – Amphibolite, amphibolite schist, metagabbro, and metabasalt undifferentiated.

X$_{bif}$ – Iron formation and Fe-rich schists, cherty quartzite, and cummingtonite-grunerite schists. Typically reddish-brown iron-stained beds. Typically shows sulfide weathering.

X$_{qc}$ – Quartzite and cherty quartzite. Medium-bedded, glassy in part.

X$_{tbd}$ – Turbidite sequences. Thin to medium-bedded greywacke to clean quartz schists. White to light grey in color.

X$_{aqm}$ – Arkosic metagreywackes with interlayered quartz-schist and minor, incomplete turbidite sequences. More micaceous but similar to unit X$_{tbd}$.

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X$_{qbg}$ – Quartz-biotite-garnet schists and metagreywacke. Graphitic in part. Similar to unit

X$_{sgw}$.

X$_{gph}$ – Dark graphitic and sulfide rich schists and shales. Highly altered in many places

with residual graphite coating. May contain garnets and or andalusite.

APPENDIX B -
Lithotectonic Units versus Stratigraphy

A major objective of this study was to provide information on stratigraphic

relationships within the Mount Rushmore Quadrangle that would be applicable to

ongoing and future investigations within the crystalline core of the Black Hills.

Published material concerning stratigraphic relationships within the Precambrian

rocks is sparse and occurs mainly in non peer-reviewed sources (e.g. USGS

Professional Papers, various field guides). In addition, the number of workers

historically and currently involved in such investigations is quite modest. Most

contemporary investigations of the Precambrian geology of the Black Hills rely on

three primary sources for stratigraphic interpretation, two of which predate the

advent of plate tectonic theory: Noble and Harder (1948) and Redden (1963,

1968). Furthermore, available data regarding the age of most of the stratigraphic

succession is temporally broad, dividing the rocks into two groups: (1) an older,

~2550 – 2480 Ma rift related sequence (Redden, 1981; Dahl et al., 2005a,b) that

is unconformably overlain by (2) ~2015 – 1885 Ma (Bekker et al, 2003: Dahl et

al., 2005a,b) continental shelf-rise, shallow-water deposits (Redden et al., 1990).

The difficulty in defining and correlating stratigraphic units with any

confidence within the crystalline Black Hills is three-fold. First, the most basic

problem is the recurrence of identical rock types within the succession and the

paucity of good stratigraphic marker units. Second, the rocks within the

crystalline core have been multiply and complexly deformed and great care must

be taken with regard to stratigraphic relationships. Thirdly, the rocks have

undergone at least two episodes of prograde metamorphism. The thermal

overprint of the Harney Peak granite has significantly altered the country rocks

within its aureole and the degree of alteration is not uniform.

Previous Work

Original stratigraphic work in the Precambrian Black Hills was carried out

to evaluate the economic opportunity related to recently discovered gold deposits

and mineralization associated with numerous pegmatite intrusions. The Lead

area in the northern Black Hills, home of the Homestake mining company, served

as a focus of investigation (e.g. Hosted and Wright, 1923; Paige, 1924;

McLaughlin, 1931; Gustafson, 1933).   Noble and Harder (1948) presented a

comprehensive study of the stratigraphy and metamorphism of the Lead area

and defined a local stratigraphy. In the 1960's, Redden (1963, 1968) mapped

two 7.5-minute quadrangles in the southwestern Black Hills as part of the USGS

study of pegmatites and other Precambrian rocks in the southern Black Hills, also

defining a local stratigraphy. Subsequent workers in the southern Black Hills

adopted the stratigraphic nomenclature of Redden.

The three primary sources mentioned above (Noble and Harder, 1948;

Redden, 1963, 1968) serve as the basis for almost all stratigraphic relationships

cited in the subsequent literature for the Precambrian Black Hills. A fourth often

cited source, Ratte and Wayland (1969), outlined stratigraphic relationships in

the Hill City quadrangle, west of the Mount Rushmore Quadrangle, and

attempted to correlate rock units with the work of Redden (1963, 1968). For

reasons outlined below, this correlation is suspect, yet has remained the type

example for correlating stratigraphy across the Black Hills. Redden et al. (1990)

outlined a tentative correlation of Precambrian rock units across the Black Hills.

However, upon careful reading of the literature from which that correlation was

derived, several glaring inconsistencies were revealed, both in the actual

correlation and its use in interpreting the structure of the Black Hills. Figure 2-1

compares the various stratigraphic interpretations of the previously cited works

along with works from Bayley (1972b, 1972c).

Noble and Harder (1948) presented the first comprehensive study of the

stratigraphy and metamorphism of the Lead district in the northern Black Hills.

The stratigraphy as defined by Noble and Harder (1948) is shown in Figure 2-2.

No attempts to correlate the Lead stratigraphy with rocks in other parts of the

Black Hills were made with the exception of the Rochford district approximately

20 miles south of Lead, where the lowermost stratigraphy was repeated (Noble

and Harder, 1948). This correlation was based on multiple lines of evidence, but

primarily on the recognition of the Homestake formation and the ore

mineralization that occurred within it. As stated by Noble and Harder (1948):

> "There is not only a repetition of distinctive formations or
> members, but a repetition of a sequence of distinctive
> formations, and the repetition of an unconformity. It is
> fortunate that the evidence for correlation is so positive, since
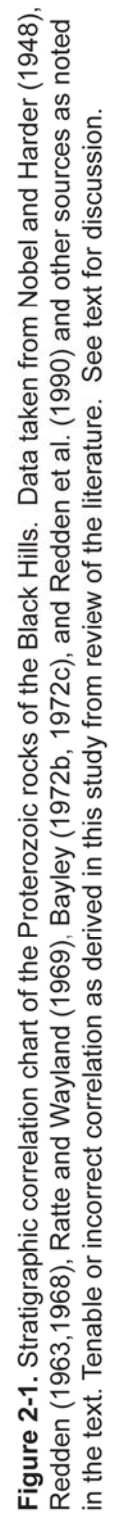> the whole stratigraphic column is upside-down."
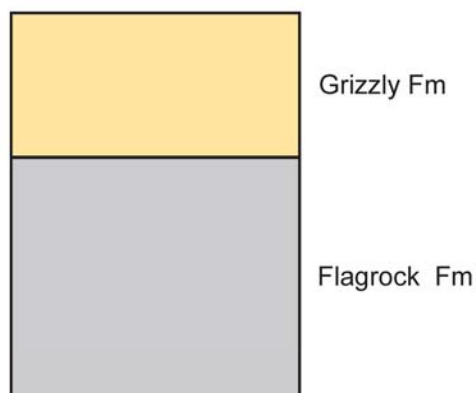
Noble and Harder (1948) went on to say:

"We know of no other area in the Black Hills which can be surely correlated with the succession at Lead."

Other authors (e.g. Runner, 1934) had suggested that the stratigraphic sequence at Lead was repeated elsewhere in the northern Black Hills, but Noble and Harder (1948) noted that these correlations were based on slight evidence and that the rock types included in the Lead district stratigraphy were not uncommon "in all Precambrian rocks of the sedimentary (Algonkian) type." They cautioned that correlation based just on similar rock types should not be made in the absence of the repetition of nearly all the sequence of the district.

Redden (1963) mapped the Four-mile quadrangle in the southwestern Black Hills. Approximately one-half of the quadrangle is underlain by Precambrian rocks, while the other half is overlain by Paleozoic and Tertiary strata. Redden defined three geologic formations in the Precambrian rocks of the Four-mile quadrangle. They are, in ascending order, the Bugtown formation, the Crow formation, and the Mayo formation (Figure 2-3a). Redden did not attempt to correlate the rocks of the Four-mile quadrangle with other rocks in the Black Hills, but did note the lithologic similarity between the Precambrian rocks of the quadrangle and those defined by Noble and Harder (1948).

Redden (1968) mapped the Berne quadrangle immediately north of the Four-mile quadrangle. The main structural element in the Berne quadrangle is the Grand Junction fault, which runs from the lower southeast side of the quadrangle slightly toward the northwest (Figure 2-3b). Redden separated

Figure 2-1. Stratigraphic correlation chart of the Proterozoic rocks of the Black Hills. Data taken from Nobel and Harder (1948), Redden (1963,1968), Ratte and Wayland (1969), Bayley (1972b, 1972c), and Redden et al. (1990) and other sources as noted in the text. Tenable or incorrect correlation as derived in this study from review of the literature. See text for discussion.
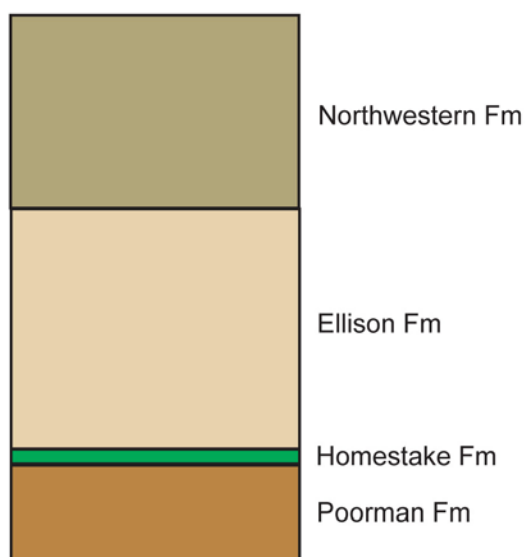
Figure 2-2. Stratigraphy of the Lead district from Noble and Harder (1948, 1949). Column has a vertical scale of 1 inch equals 4,000 feet. The thickness of all formations are best estimates from the literature. The upper contact of the Grizzly formation is an unconformity and the bottom of the Poorman formation does not outcrop so thickness are approximate.

the rocks of the Berne quadrangle into two groups: (1) rocks to the west of the Grand Junction fault; and, (2) those east of the Grand Junction fault. Rocks located west of the Grand Junction fault were divided into the three formations defined by Redden (1963) in the Four-mile quadrangle, and two previously undefined formations: the Vanderlehr formation and the Loues formation. The complete stratigraphy of the rocks located west of the Grand Junction fault as defined by Redden is shown in Figure 2-3b. Redden divided the rocks of the

Figure 2-3. Stratigraphic relations of (A) the Four-Mile quadrangle (Redden, 1963) and (B) Berne quadrangle (Redden, 1968). Compare with Figure 2-1. Note that the Loues Fm is correlative to the Flagrock Fm and that the Vanderlehr Fm is correlative with the Poorman Fm of of Noble and Harder (1948, 1949). Redden (1968) makes the correlation and this contact conformable in the Berne quadrangle despite the fact that a major unconformity exists in the Lead district and over 7,000 feet of the Homestake, Ellison, and Northwestern Fms are missing in the Berne quadrangle. The stratigraphic columns have a vertical scale of 1 inch equals 2000 feet.

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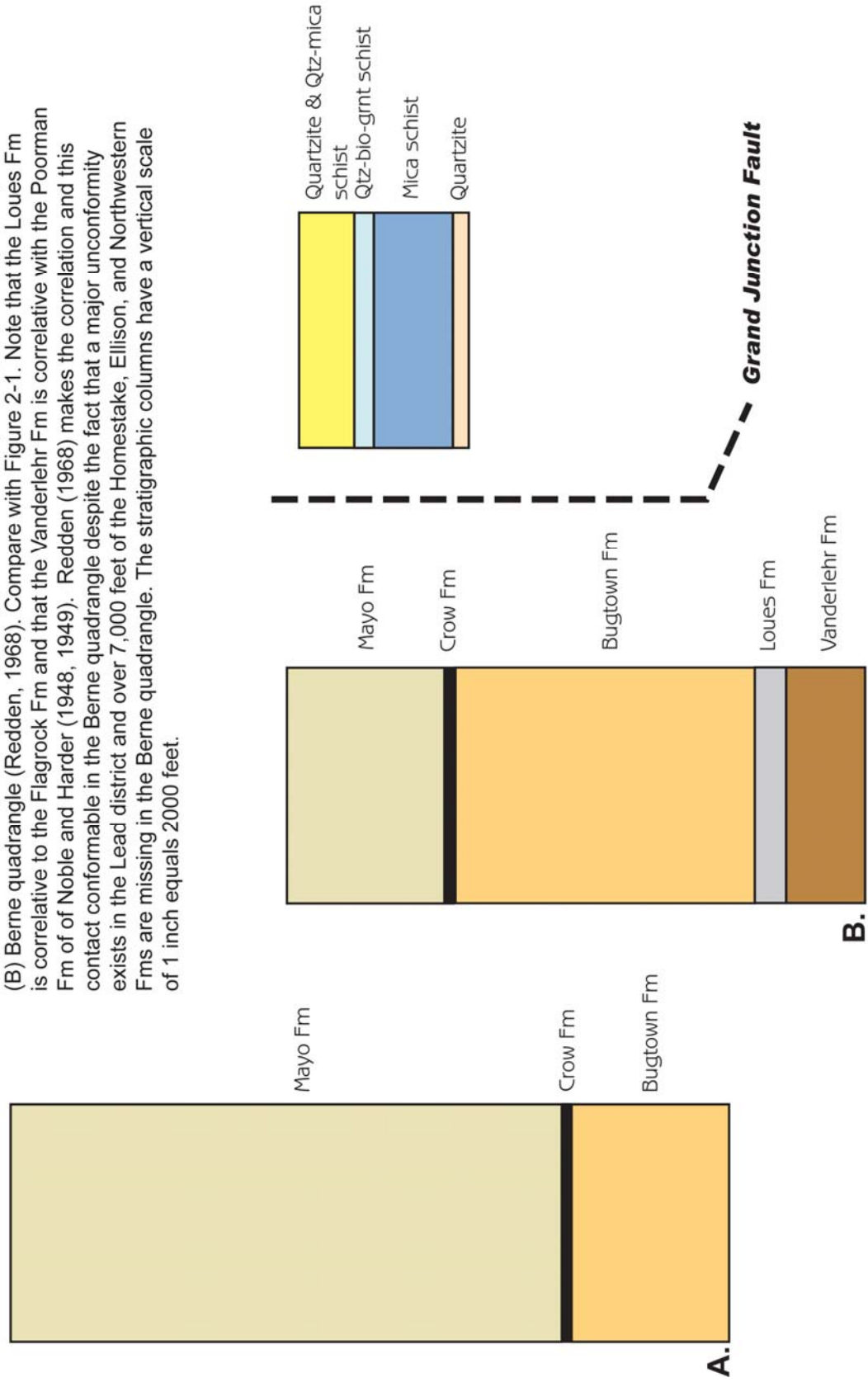
Berne quadrangle located east of the Grand Junction fault into four separate units as shown in Figure 2-3b. Redden stated that the stratigraphic relationship of these four units was not fully known nor had any genetic relationship been established across the Grand Junction fault. However, he attempted to correlate the rock units on either side of the fault based solely upon lithologic similarity.

Ratte and Wayland (1969) divided the rocks of the Hill City quadrangle (Figure 2-4) into two formations: the Bugtown formation as defined by Redden (1963) and the previously undefined Oreville formation. The stratigraphy of the Hill City quadrangle as defined by Ratte and Wayland (1969) is shown in (Figure 2-4). The adoption of the Bugtown formational name for metagraywackes, quartz-mica schists, and phyllites in the Hill City quadrangle was made seemingly without regard to the tenuous and somewhat speculative correlation of rock units across the Grand Junction fault in the Berne quadrangle. Ratte and Wayland (1969) did not address this concern in their report. However, they did recognize the problem using their own Oreville formation in correlating rocks of similar lithology across the Hill City quadrangle. Most notably, they pointed out that rocks "of Oreville lithology" in the northeast corner of the quadrangle (across the Empire Mine-Keystone fault system) were not necessarily correlative with Oreville-type rocks elsewhere in quadrangle. Norton (1974) correlated the Oreville formation with the Swede Gulch Formation of Bayley (1972) and then correlated the Swede Gulch with the Grizzly Formation of Noble and Harder (1948).

Bugtown Fm

Figure 2-4. Stratigraphiy of the Hill City quadrangle from Ratte and Wayland (1969). The adoption of the Bugtown formational name is problematic and is based on the speculative correlation of rocks across the Grand Junction Fault (Redden, 1968). Ratte and Wayland (1969) defined the Oreville Fm but noted its limitations in correlating rocks of similar lithology across the Hill City quadrangle. Vertical scale is 1 inch equals 2000 ft.

Oreville Fm

Redden et al. (1990) proffered a first-order assessment of stratigraphic relationships for all of the crystalline rocks of the Black Hills. This correlation included the seminal papers mentioned above and also the work of Hosted and Wright (1923), Bayley (1972, 1972b), and Redden (1981). The exact reasoning behind correlating the different stratigraphies across the Black Hills is not well explained, and seems in large part based on the unpublished work of Redden or master's theses directed by Redden. Many of the assertions and correlations of Redden et al. (1990) remain unclear and subject to much debate. Norton (1974) stated that neither during work on the Berne quadrangle (Redden, 1968), nor during subsequent mapping of adjacent areas, had a persuasive correlation been made between rocks on either side of the Grand Junction Fault. The tentative correlation of Redden et al. (1990) is reproduced in Table 2-1.

Problems with stratigraphic correlation

Stratigraphic relationships must exist within the metasedimentary sequences of rocks in the Black Hills. Previous studies (e.g. Noble and Harder, 1948; Redden, 1963, 1968) have demonstrated that sufficient evidence exists to establish stratigraphic relationships, at least locally, for parts of the crystalline Black Hills. However, even the local stratigraphies are subject to certain ambiguities that are compounded when trying to correlate locally derived stratigraphic relationships from different parts of the Black Hills. Among the most fundamental problems are lack of distinct marker units and sequences, recognition of stratigraphic younging criteria, repetition of similar rock units, facies changes, and complex and incompletely understood structural relationships.

Noble and Harder (1948, 1949) recognized the perils of interpreting a stratigraphic succession in the Precambrian rocks of the Black Hills and using it to interpret structure. They cautioned that changes in their stratigraphic interpretation would necessitate a major revision of the structure. Ratte and Wayland (1969) echoed this premise regarding the use of preserved primary structures and their interaction with tight minor folds as stratigraphic younging criteria. Locally and for brief distances in the field, relict primary stratigraphic structures such as graded bedding, load casts, and cross-beds can be used to determine the direction of stratigraphic younging. However, the complexity of

multiple fold generations and incomplete exposure can lead to erroneous assumptions without careful and consistent observation. Woodland (1979) also recognized difficulties in lithologic correlation with previously defined units and suggested that facies changes in lithologic members and soft-sediment deformation further exacerbated the potential for errors in structural interpretation based on proposed stratigraphic sequences. Furthermore, the occurrence of primary sedimentary structures is not consistent and varies considerably with lithology and even location.

Throughout most of the crystalline Black Hills, there is a paucity of traceable stratigraphic marker units, while there is an abundance of similar, indistinct rock types. Noble and Harder (1948) relied on the distinctive Homestake formation to develop their stratigraphy. They described the majority rock type present in the other formations as gray phyllites and commented on the absence of appropriate marker units. Redden (1963) relied on the distinctive Crow formation to delineate between the quartz-mica schists of his Bugtown formation and the lithologically similar Mayo formation. Ratte and Wayland (1969) relied on gross lithology to separate the rocks in the Hill City quadrangle: thick bedded metagraywackes with inter-layered quartz-mica schists and phyllites of the "Bugtown formation" and the mica-schists of the Oreville formation. They also acknowledged the uncertainty in calling all similar sequences of mica-schist Oreville formation, most notably they singled out the rocks northeast of the Empire Mine fault. Even within the defined local stratigraphies, there may be multiple units that are so lithologically similar as to

be indistinguishable. Furthermore, distinct sequences of deposition are virtually absent. Relative thickness of units and overall lithologic variation may be primarily controlled by subsequent deformation. For example, an inter-layered sequence of greywacke and shale may show a totally different ratio of greywacke to shale in the limbs of major folds as compared to the noses of the folds, giving the overall impression of two distinctive depositional regimes, while in fact only one existed.

Perhaps the most obvious demonstrations of the difficulty associated in correlating stratigraphy in the Precambrian Black Hills rocks is found in the geologic map of Redden et al. (1990; Figure 2-5). This map is a simplified version of Dewitt et al. (1989) 1:250,000-scale map of the Black Hills and has essentially the same description of map units. Table 2-1 reproduces the description of map units for the map of Redden et al. (1990). Some subtle but very enlightening discrepancies appear in the explanation as well as the tentative correlation of stratigraphies presented in Table 2-1. If one assumes the correlations of Redden et al. (1990) to be correct, the map explanation and hence the overall map must be incorrect with respect to the correlations and previous work. The following is a partial list of incorrect relationships derived from the descriptions of the map units and stratigraphic correlations as proposed by Redden et al. (1990; c.f. Figure 2-5, Table 2-1) based on comparison with the earlier published work (e.g. Noble and Harder, 1948; Redden, 1963, 1968; Ratte and Wayland, 1969):

1. Unit Xps includes part of the Oreville formation but overlies unit Xc which is Crow formation. Ratte and Wayland (1969) clearly indicate that the Oreville formation is older than the Bugtown formation. Redden clearly indicates (1963, 1968) that the Bugtown formation is conformably overlain by the Crow formation.

2. Unit Xps then cannot be the youngest metasedimentary unit. Unit Xqg includes part of the Ellison formation (Noble and Harder, 1948), the top of which is marked by an unconformity. This unit overlies unit Xbs of the Oreville formation of Ratte and Wayland (1969). The Oreville formation must occur above this unconformity based on Redden (1963, 1968) and Ratte and Wayland (1969).

3. Unit Xgw breaks out the graywackes from four different stratigraphic units that are not equivalent: Roubaix formation (Bayley, 1972b), Mayo and Bugtown formations (Redden, 1968) and the Zimmer Ridge member of the Oreville formation (Ratte and Wayland, 1969); and lumps them based on similar rock type. The map pattern and structure resolved from this is suspect, especially if one assumes the stratigraphy correlative. Either the structure (as depicted) is correct and the stratigraphic relationships incorrect, or vice versa. Both cannot be correct.

Figure 2-5. Reproduction of the simplified geologic map of Precambrian units in the Black Hills from Redden et al. (1990).

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Table 2-1. Description of map units for Figure 2-5. Reproduced from Redden et al. (1990).

| Ti | Tertiary igneous rocks |

| Pr | Phanerozoic rocks |

Early Proterozoic

| Xh | Harney Peak granite. Coarse-grained to pegmatitic muscovite granite and pegmatite |

| Xps | Phyllite and slate. Mica schist in Lead area. Includes Grizzly Fm (Dodge, 1942), Swede Gulch Fm (Bayley, 1972), part of the lower Oreville Fm (Ratte and Wayland, 1969), and a large area of rocks in the core of the Black Hills |

| Xc | Biotite schist, calcsilicate gneiss, and amphibolite. Crow Fm (Redden, 1963) wouthwest of Custer |

| Xgb | Metagabbro. Sills and dikes of amphibolite or greenstone. At least two separate ages (~1,883 Ma and 1,964 Ma) known and younger metagabbro intrudes the 1,884 Ma unit Xpb |

| Xpb | Phyllite and biotite schist. Contains minor chert and amphibole-bearing rocks. Locally intruded by thin sills of metagabbro. Includes Poverty Gulch slate, Nahant schist, and Irish Gulch slate in the Rochford area (Bayley, 1972) and Northwestern and Flagro |

| Xms | Muscovite schist and phyllite. Includes part of the Oreville Fm. Equivalent to unit Xpb in Rochford and Lead areas. |

| Xqg | Quartzite and metagraywacke. Quartzite and siliceous schist. Includes Ellison Fm in the Lead area, Moonshine Gulch quartzite north of Rochford, and siliceous graywacke west of Rochford. Possibly equivalent in part to Xgw and Xcg in central Black Hills. U |

| Xbs | Biotite schist or phyllite. Thin bedded and commonly garnet-rich schist. Largely includes parts of the Oreville Formation |

| Xcg | Conglomeratic biotite schist and phyllite. Also siliceous biotite phyllite, garnetiferous schist, quartite, and carbonate-silica iron-formation. Unconformable lower contact |

| Xby | Metabasalt near Rockerville. Includes metabasalt in Rochford, Lead, and Rockerville areas |

| Xgw | Metagraywacke. Siliceous mica schist and impure quartzite at repeated stratigraphic intervals. Includes part of Roubaix Fm (Bayley, 1972b), Mayo and Bugtown Fms (Redden, 1968), and members of the Oreville Fm as well as unamed units in the central Black Hi |

| Xb | Metabasalt. Amphibolite, greenstone, and actinolite schist. Included are Hay Creek Greenstone (Bayley, 1972c) and part of the Vanderlehr Fm (Redden, 1968) |

| Xif | Iron formation. Iron formation, ferruginous chert, and minor mica schist. Included are Homestake Fm, Rochford Fm and Montana Mine Fm, and iron-formation in the Keystone area and in minor areas throughout the Precambrian core of the Black Hills |

| Xsc | Siliceous biotite phyllite, calcareous biotite phyllite, and schist. Includes the Poorman Fm (Hosted Wright, 1923) and Reausaw slate (Bayley, 1972b) which intertongue with meta basalt Xb |

| Xd | Dolomitic marble and schist. Marble, phyllite, and calcareous phyllite. Includes the Roberts Draw Fm in the Nemo area (Redden, 1981) and part of the Vanderlehr Fm at Bear Mountain |

| Xqc | Quartzite and metaconglomerate. In the Nemo area, map unit includes taconite conglomerate and is equivalent to the Estes Fm (Redden, 1981). In the eastern and southeastern Black Hills, map unit includes Buck Mtn quartzite (Redden, 1981) and Gingrass Draw |

Unconformity

| Xlg | Layer metagabbro. Gravity differentiated Blue Draw Metagabbro sill (2,700 Ma; Redden, 1981) |

| Xcq | Metaconglomerate and quartzite. Includes the Boxelder Creek Fm, Benchmark Iron-Fm (Redden, 1981), and an unnamed carbonate-silicate-oxide facies iron-formation along the west side of the Nemo area. |

Unconformity

Archean

| Wgr | Granite. Granite and gneissic granite. Includes Little Elk Granite and the granite at Bear Mountain |

| Wos | Older metasedimentary rocks. Includes Nemo iron-formation and schist at Tinton area. |

4. Unit Xsc is described as equivalent to the Poorman formation (Noble and Harder, 1948) but it overlies unit Xqc which is equivalent to the Estes formation (Redden, 1981) and the Montana Mine formation (Bayley, 1972b), both of which are supposed to be stratigraphically younger.

5. Parts of the Oreville formation as defined by Ratte and Wayland (1969) appear in four different mapped units that occur at different stratigraphic intervals: Xps, Xms, Xbs, and Xgw

If one assumes that the correlated stratigraphy is correct and then rearranges the explanation of map units given by Redden et al. (1990) to amend the discrepancies mentioned above, a whole new set of problems arise. If the process is repeated, the effort becomes a shell game for which there seems to be no unique solution. The use of the assumed correlations to interpret the structural relationships within the Black Hills further complicates the conundrum until one must rely on abstruse stratigraphic, structural, and tectonic relationships to explain the overall pattern.

The root of the problem is not the total lack of stratigraphy, but the presence of local stratigraphies that do not seem to correlate across major fault boundaries. Furthermore, attempts to do so have become mired in terminology such as "Bugtown" or "Oreville" formational names, and hence a genetic relationship is implied where one does not likely exist. The abundance of similar rock types and the disposition of previous workers to assign formational names with little corroborating evidence except for similar lithologic characteristics is demonstrated above. Thus, a stratigraphy has evolved and has been applied

across the Black Hills that is inconsistent within itself, yet has remained

unchallenged in the literature. Moreover, there is also clear evidence for the

major structural features and relationships of the Precambrian Black Hills, yet the

stratigraphic nomenclature used within the Black Hills is inconsistent with respect

to the structural relationships. Hence, it is apparent that the overall stratigraphic

relationships within the Black Hills cannot be integrated as easily as has been

proposed in the literature.

It is clear from the map descriptions of Redden et al. (1990; Table 2-1)

that either the stratigraphic correlations are not viable or the mapped structure is

incorrect. There is strong evidence for the overall structural patterns shown in

Figure 2-5. It is also evident from careful reading of the literature and of Table 2-

1 that ingrained stratigraphic nomenclature used across the Black Hills must be

incorrect. The similarity of rock types and depositional successions coupled with

the lack of distinct marker units over much of the Black Hills has lead previous

workers to construct an over-arching stratigraphic framework that does not exist

in the Precambrian Black Hills.

APPENDIX C- Thin Section Locations
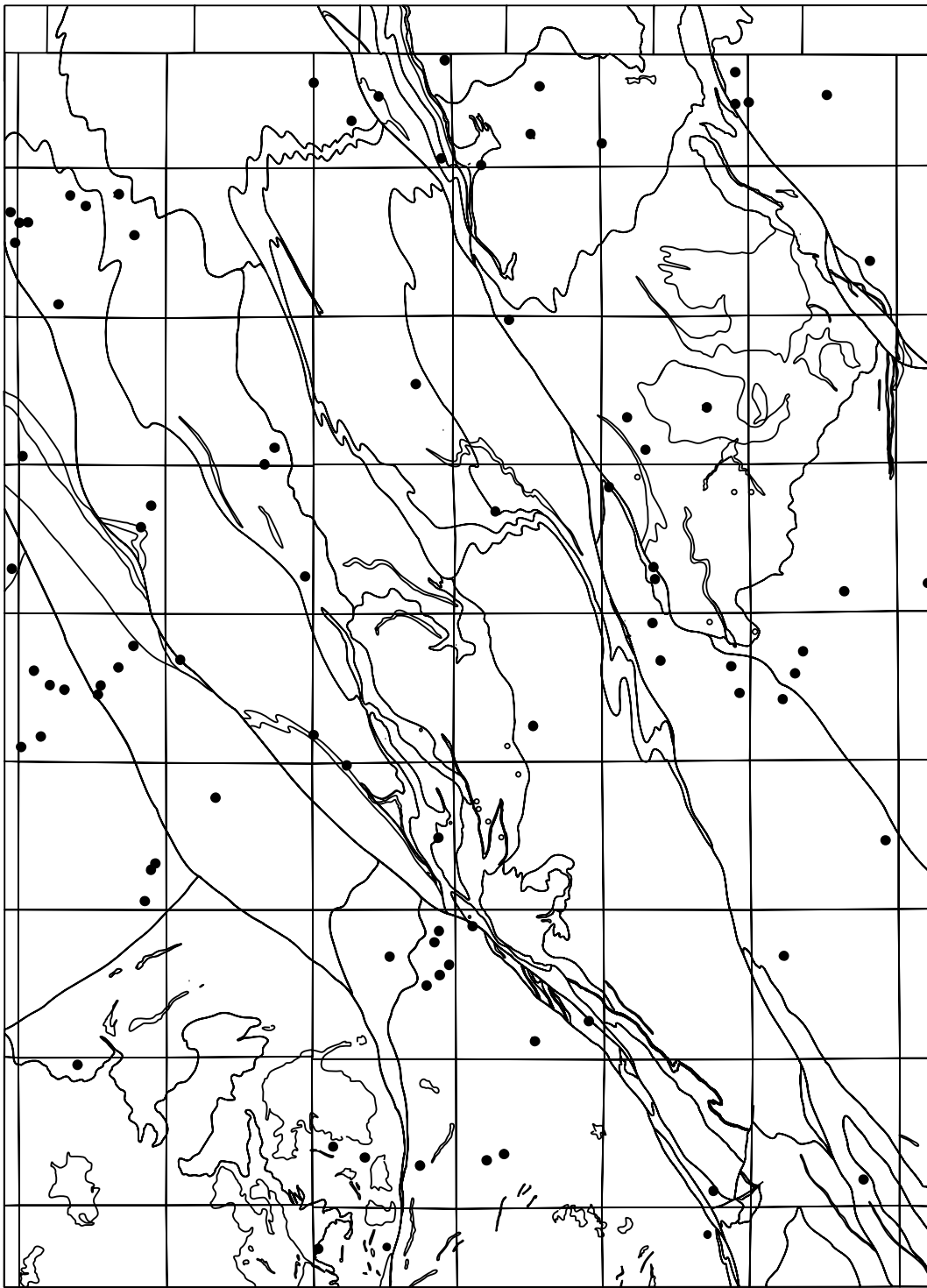
Outline map of the Mount Rushmore Quadrangle. Each dot represents a thin-sectioned sample from this study. Compare with Plate II (station numbers) for exact sample numbers. Samples from Drs. Bauer and Nabelek not shown.

Vita

Joseph Christopher Hill was born to Earl W. and Lorene R. Hill in Oak Ridge, Tennessee on April 11, 1969. He is the youngest of eight children. Joe grew up on his family's farm near the Clinch River just outside Clinton, Tennessee. He graduated from Anderson County High School in June, 1987. In 1995, Joe decided to also pursue a degree in Geology and found his calling. He graduated with a Bachelor of Science in geology in 1996 and earned a Masters of Science degree in Structural Geology in 1999, both from the Department of Earth and Planetary Sciences, University of Tennessee-Knoxville. Joe was married September 5, 1998 to Kristin Leigh Taylor, a beautiful brunette from Conyers, Georgia who's love of animals and the outdoors eclipsed his own. In the Fall of 1999, Joe and Kristin moved to Columbia, Missouri to complete Joe's graduate work in geology. While in Missouri, they had a beautiful baby boy, Aidan Christopher, on October 11. Joe accepted a tenure-track job in 2004, defended his dissertation in 2006, and is currently a Professor of Geology at Bloomsburg University of Pennsylvania and the family relocated to Pennsylvania. He hates to refer to himself in third person.