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Ar-40/Ar-39 Evidence for Middle Proterozoic (1300-1500 Ma) Slow Cooling of the Southern Black Hills, South Dakota, Midcontinent, North America: Implications for Early Proterozoic P-T Evolution and Posttectonic Magmatism

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$^{40}Ar/^{39}Ar$ evidence for Middle Proterozoic (1300-1500 Ma) slow cooling of the southern Black Hills, South Dakota, midcontinent, North America: Implications for Early Proterozoic P-T evolution and posttectonic magmatism

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Abstract. $^{40}Ar/^{39}Ar$ total gas and plateau dates from muscovite and biotite in the southern Black Hills, South Dakota, provide evidence for a period of Middle Proterozoic slow cooling. Early Proterozoic (1600-1650 Ma) mica dates were obtained from metasedimentary rocks located in a synformal structure between the Harney Peak and Bear Mountain domes and also south of Bear Mountain. Metamorphic rocks from the dome areas and undeformed samples of the ~1710 Ma Harney Peak Granite (HPG) yield Middle Proterozoic mica dates (~1270-1500 Ma). Two samples collected between the synform and Bear Mountain dome yield intermediate total gas mica dates of ~1550 Ma. We suggest two end-member interpretations to explain the map pattern of cooling ages: (1) subhorizontal slow cooling of an area which exhibits variation in mica Ar retention intervals or (2) mild folding of a Middle Proterozoic (~1500 Ma) ~300°C isotherm. According to the second interpretation, the preservation of older dates between the domes may reflect reactivation of a preexisting synformal structure (and downwarping of relatively cold rocks) during a period of approximately east-west contraction and slow uplift during the Middle Proterozoic. The mica data, together with hornblende data from the Black Hills published elsewhere, indicate that the ambient country-rock temperature at the 3-4 kbar depth of emplacement of the HPG was between 350°C and 500°C, suggesting that the average upper crustal geothermal gradient was 25°-40°C/km prior to intrusion. The thermochronologic data suggest HPG emplacement was followed by a ~200 m.y. period of stability and tectonic quiescence with little uplift. We propose that crust thickened during the Early Proterozoic was uplifted and erosionally(?) thinned prior to ~1710 Ma and that the HPG magma was emplaced into isostatically stable crust of relatively normal thickness. We speculate that uplift and crustal thinning prior to HPG intrusion was the result of differential thinning of the subcrustal lithosphere beneath the Black Hills. If so, this process would have also caused an increase in mantle heat flux across the Moho and triggered vapor-absent melting of biotite to produce the HPG magma. This scenario for posttectonic granite generation is supported, in part, by the fact that in the whole of the Black Hills, the HPG is spatially associated with the deepest exposed Early Proterozoic country rock.

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1. Introduction

The dominant Precambrian tectonic elements making up the southern portion of Laurentia (between the Grenville and Cordilleran Orogens, Figure 1) were rapidly formed and/or assembled toward the end of the Early Proterozoic (1900-1600 Ma). Preferentially intruded into the Early Proterozoic collisional/accretionary belts of this region are numerous anorogenic or posttectonic plutons whose origins remain controversial [*Hoffman*, 1989a; *Windley*, 1993; *Nyman et al.*, 1994; *Holm and Lux*, 1996]. The purpose of this study has been to investigate the postcollisional intrusive and thermal history of Early Proterozoic metamorphic rocks in the Black Hills of southwestern South Dakota, United States of America. On the basis of regional geophysical features, the crystalline basement exposed in the Black Hills represents the southernmost exposure of the Early Proterozoic Trans-Hudson orogen near its termination by the younger Central Plains orogen (locality BH, Figure 1). However, the Black Hills represent the only exposure of the geophysically defined Trans-Hudson orogenic belt for over 1000 km along strike, and the lithologic units and timing of tectonic and intrusive events there appear fundamentally different from much of the Trans-Hudson orogen in Canada [i.e., *Redden and DeWitt*, 1996]. For instance, the ~1710 Ma posttectonic Harney Peak Granite in the Black Hills is 60-70 m.y. younger than posttectonic granites and pegmatites in the Saskatchewan (Canada) segment of the orogen [*Bickford et al.*, 1990], leading some to suggest that the Harney Peak Granite may actually be related to Central Plains orogen suturing [*Sims et al.*, 1991].

During the last decade, new and improved petrologic and thermochronologic techniques have greatly increased our understanding of the midcrustal processes which play an integral role in the growth and stabilization of Precambrian crust [i.e., *Bowring and Karlstrom*, 1990; *Hodges et al.*, 1994; *Williams and Karlstrom*, 1996]. Reconstruction of pressure-temperature-time paths of Proterozoic juvenile rocks in the southwestern United States has led to recognition of their long-term midcrustal residence throughout a significant portion of the Proterozoic. Evidence in that region for protracted (300-400 m.y.) midcrustal cooling has important implications for crustal evolution and craton development during the Proterozoic [*Bowring et al.*, 1996]. In constrast, very little is known about the timing or the mechanism by which midcrustal Early Proterozoic rocks of the Black Hills were exhumed and cooled. Previous investigations of

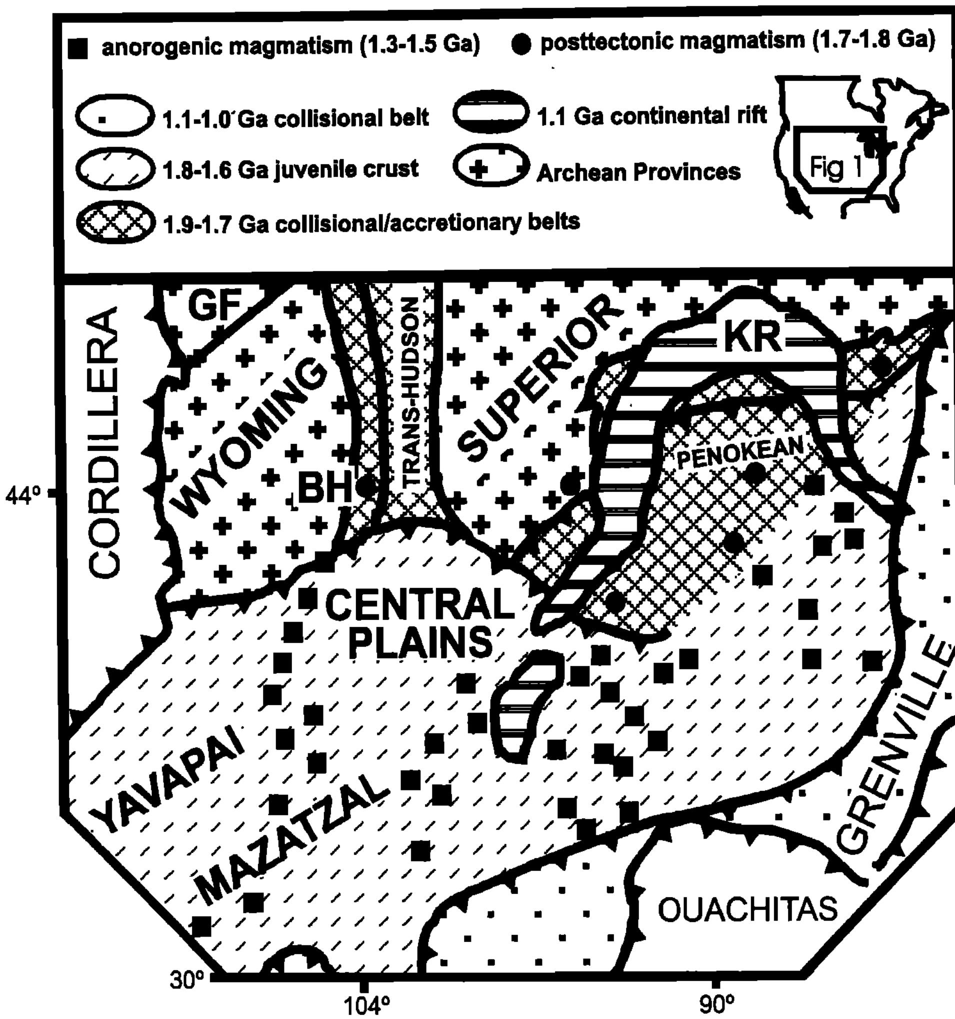

Figure 1. Precambrian tectonic elements of the southern portion of the North American craton (modified after *Hoffman* [1989b]). Inset shows the location within North America. Abbreviations are as follows: BH, Black Hills inlier and location of Figure 2; GF, Great Falls tectonic zone; and KR, Keweenawan rift.

these rocks have focused principally on the tectonic setting in which they were initially formed at the surface and the subsequent conditions and overall tectonic framework in which they were buried and metamorphosed [e.g., *Redden et al.*, 1990; *Terry and Friberg*, 1990; *Helms and Labotka*, 1991; *Friberg et al.*, 1996]. In this study, we have used $^{40}Ar/^{39}Ar$ thermochronology to investigate the postcollisional cooling history of this important Early Proterozoic orogenic belt.

Determining the initial cooling history of Proterozoic orogenic crust can sometimes be difficult because of thermal overprinting associated with younger events and/or relatively poor exposure. Such has certainly been the case in the northern Black Hills where abundant Tertiary igneous rocks have been responsible for at least partial resetting of Rb-Sr mineral ages [*Zartman et al.*, 1964]. In contrast, Tertiary igneous rocks are absent in the southern Black Hills, and Rb-Sr mineral ages are, for the most part, substantially older [*Riley*, 1970a; *Walker et al.*, 1986]. In addition, rocks of the southern Black Hills are relatively well-exposed and consist of coarse-grained metasedimentary and igneous rocks that contain abundant muscovite and biotite. Finally, the Early Proterozoic metamorphism and deformation in the southern Black Hills culminated with the emplacement of a large, well-dated granite/pegmatite intrusion, the 1710 Ma Harney Peak Granite (hereafter referred to as HPG). The widespread thermal effects imposed by the granite on the country rocks throughout the southern Black Hills are well documented from metamorphic studies [*Helms and Labotka*, 1991; *Terry and Friberg*, 1990; *Friberg et al.*, 1996]. Because the pre-1710 Ma metamorphic history of the region is difficult to assess because of thermal overprinting, only the post-1710 Ma, lower-temperature cooling history is addressed here. We present evidence for prolonged midcrustal (3-4 kbar) residence and very slow cooling during the Middle Proterozoic. As for the Early Proterozoic accretionary belts to the south, documentation of a protracted midcrustal cooling history has, we believe, important implications for both the Middle and Early Proterozoic tectonothermal evolution of this region and for genesis of the posttectonic Harney Peak Granite.

2. Geologic Setting

The Black Hills crystalline core consists of multiply deformed and metamorphosed Early Proterozoic rocks exposed between the Archean Superior Province to the east and the Archean Wyoming

Province to the west (Figure 1). Remnants of Archean rocks in the Black Hills (Figure 2) suggest this region is part of the Wyoming craton which has been reworked during Early Proterozoic tectonism [*Gosselin et al.*, 1988]. The basement rocks are composed dominantly of a thick sequence of Early Proterozoic clastic metasedimentary rocks and minor mafic volcanic and plutonic rocks. The entire sequence, which contains tuffs and gabbros as young as 1883±5 Ma [*Redden et al.*, 1990], was tectonically buried, deformed, and metamorphosed prior to being intruded by the posttectonic HPG at ~1710 Ma [*DeWitt et al.*, 1986; *Terry and Friberg*, 1990]. Sills from the main granite body have yielded an Rb-Sr whole rock isochron of 1711±21 Ma [*Riley*, 1970a; *Walker et al.*, 1986] and a U-Pb monazite date of 1715±3 Ma [*Redden et al.*, 1990]. Associated pegmatites which surround the main portion of the pluton yield U-Pb apatite dates of 1706±4.4 Ma to 1695±3 Ma [*Krogstad and Walker*, 1994]. The crystalline core is nonconformably overlain by Phanerozoic sedimentary rocks, indicating its exposure by Cambrian time, and was ultimately reexposed by Laramide doming.

The main 1880-1710 Ma structural elements in the core of the Black Hills are northdirected, ENE striking fold nappes/thrusts (F1) that were refolded into NNW striking upright folds (F2) accompanied by the development of a locally penetrative axial planar foliation [*Redden and Norton*, 1975; *DeWitt et al.*, 1986]. Structures developed during D1 and D2 deformations were modified during the subsequent mesozonal granite emplacement at 1710 Ma [*Redden et al.*, 1990]. Structural doming and localized folding (F3) of metamorphic country rocks accompanied granite emplacement, but the granite itself is largely undeformed [*Redden et al.*, 1990]. However, a late (post-HPG) northeast trending, widespread but nonpenetrative foliation (S4) of uncertain origin has been recognized by *Redden et al.* [1990].

Of the rocks exposed throughout the Black Hills, the southern region contains the deepest crustal levels. In this region, widespread metapelites, amphibolites, and quartz veins have yielded metamorphic pressures as high as 5-7 kbar [*Terry and Friberg*, 1990; *Duke et al.*, 1990a; *Terry et al.*, 1994]. In contrast, metamorphic pressures to the north are invariably 2-5 kbar [see *Duke et al.*, 1990b; *Kath and Redden*, 1990]. In the south, the 1880-1710 Ma, medium-pressure regional metamorphism was variably overprinted by a prograde low-pressure, high-temperature contact metamorphism associated with

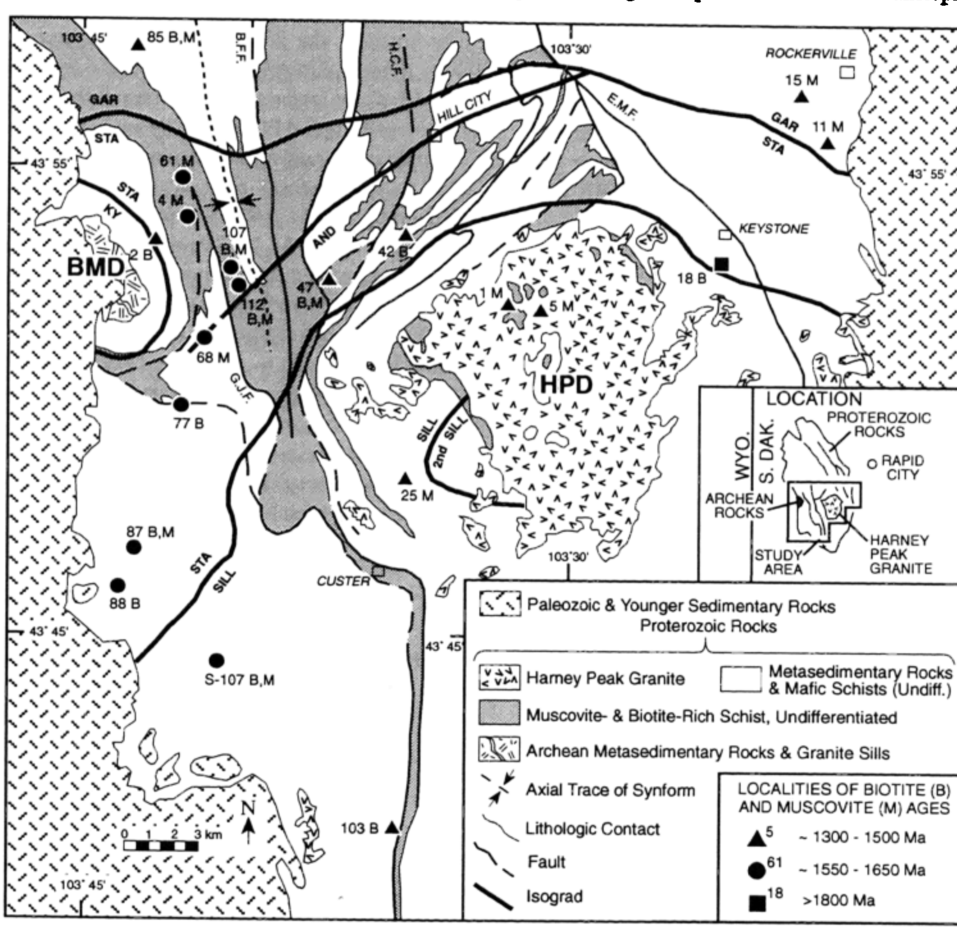

Figure 2. Generalized map of the southern Black Hills, South Dakota, showing locations of the mica-bearing schists and granites dated in this study (geology from *DeWitt et al.* [1989] and *Redden et al.* [1990]). Sample location symbols are coded for $^{40}Ar/^{39}Ar$ mica cooling ages. Muscovite- and biotite-rich schists (units Xms and Xbs of *DeWitt et al.* [1989]) delineate the fault-bounded synform structure situated between the Harney Peak dome (HPD) and the Bear Mountain dome (BMD). GJF is Grand Junction Fault, HCF is Hill City Fault, BFF is Burnt Fork Fault, and EMF.is Empire Mine Fault. Inset shows the location of the study area with respect to the crystalline basement exposure of the entire Black Hills in southwestern South Dakota.

emplacement of the HPG [*Helms and Labotka*, 1991]. At the Bear Mountain dome, for example, thermobarometry indicates peak metamorphic conditions for kyanite-bearing Early Proterozoic metasedimentary rocks of 6.5 kbar and temperatures of ~600°C [*Terry and Friberg*, 1990; *Terry et al.*, 1994], with garnet rims yielding final equilibration pressures of 4.4 kbar and temperatures of 530°C [*Helms and Labotka*, 1991]. Also, metapelites from the Harney Peak dome yield peak metamorphic conditions of 4.5-5.0 kbar and ~620°C and garnet rim equilibration conditions of 3.0-3.5 kbar and ~550°C [*Terry*, 1990; *Helms and Labotka*, 1991].

Isotopic data indicate that the interior granites of the HPG pluton were derived from vapor-absent melting of biotite in deep-seated Archean/Proterozoic metasedimentary rocks [*Walker et al.*, 1986; *Nabelek et al.*, 1992a, b; *Nabelek*, 1994]. Abundant mineralogic and thermobarometric data from the country rock exposed around the pluton indicate final emplacement at 3-4 kbars [*Redden et al.*, 1985; *Helms and Labotka*, 1991]. Both geophysical data and geologic mapping indicate that the HPG consists of a series of sheet-like intrusions with a base at relatively shallow (less than a few kilometers) crustal depths [*Redden et al.*, 1982; *Duke et al.*, 1990a; *Klasner and King*, 1990]. Although not exposed in the Bear Mountain dome area, geophysical data suggest HPG exists there not far below the surface [*Duke et al.*, 1990a; see also *DeWitt et al.*, 1989]. Field mapping suggests that the rocks between the Harney Peak and Bear Mountain domes were structurally inverted from a D2 antiform into a synform when the HPG was emplaced [*DeWitt et al.*, 1989].

3. Previous Thermochronology

Wetherill et al. [1956] obtained K-Ar ages on Harney Peak pegmatite minerals from the Bob Ingersoll Mine located north of the Harney Peak dome (Figure 1). Using the decay constants of *Steiger and Jäger* [1977], their data gave dates of 1510 Ma for muscovite, 1360 Ma for lepidolite, and 1080 Ma for microcline. *Goldich et al.* [1966] reported two (recalculated) K-Ar dates for muscovite from the HPG of 1570 Ma and 1610 Ma.

Riley [1970a, b] recognized discrepancies in Rb-Sr mineral dates from the HPG and its associated pegmatites. Pegmatite micas, microcline, and pollucite gave dates from 1575 Ma to 1695 Ma when an initial $^{87}Sr/^{86}Sr$ of 0.714 was assumed [*Walker et al.*, 1986]. A similar Rb-Sr date of 1680±25 Ma (2σ) on muscovite from boudin fracture fillings near the flank of Bear Mountain dome [*Ratté*, 1986] is commonly interpreted to represent the approximate time of dome formation [*Redden et al.*, 1990; *Terry and Friberg*, 1990]. However, *Ratté and Zartman* [1970] also reported a much younger muscovite Rb-Sr date of 1560 Ma from a muscovite schist sample collected northeast of the Bear Mountain dome.

More recently, *Redden et al.* [1990] obtained Rb-Sr whole rock isochron dates from a metatuff and a metagraywacke collected from the central and northern Black Hills. The metatuff gave a 1534±50 Ma (2σ) date and the metagraywacke gave a 1572±89 Ma (2σ) date. *Redden et al.* [1990] tentatively suggested that the pooled age of 1543±43 Ma (2σ) for these two samples may represent the time of formation of the weak, northeast trending, S4 foliation found throughout much of the Black Hills.

4. Methodology

In order to determine the cooling age pattern across the southern Black Hills, samples of the HPG and the metasedimentary rocks were selected from widely spaced localities (Figure 2). Eighteen medium-grained pelitic schists and metagraywackes were sampled from the garnet, staurolite, and sillimanite zones surrounding the HPG [*Dahl et al.*, 1993]. Petrographic analysis reveals that the micas are typically unaltered, with only minor hematite or chlorite alteration of biotite. The majority of the rocks sampled contain one well-developed foliation. In the majority of samples, biotite is somewhat coarser grained than coexisting muscovite (i.e., 0.1-0.4 x 0.01-0.02 mm for muscovite versus 0.1-0.5 x 0.01-0.05 mm for biotite). In some of the samples (S-107, S-103, ST-107, and ST-112), late, coarser-grained (0.3-0.5 x 0.1-0.2 mm), randomly oriented micas overgrow the primary foliation. These late micas constitute <5% (by volume) of total muscovite or biotite in each sample.

Mica separates were obtained using standard magnetic separation techniques combined with paper separation and handpicking. The coarsest possible grain size lacking composite grains (usually the 250-180 μm range) was chosen for dating. Purity of approximately 99% was obtained by these procedures, as verified by petrographic examination and confirmed by Inductively Coupled Plasma (ICP) analysis [*Dahl et al.*, 1993].

Sample preparation, irradiation, and analytical procedures for $^{40}Ar/^{39}Ar$ incremental release dating follows the procedures described by *Lux* [1986]. Samples were encapsulated in tin foil and irradiated in the L67 facility of the Ford Reactor at the Phoenix Memorial Laboratory reactor of the University of Michigan. Variations in neutron flux during irradiation were monitored with the University of Maine flux monitor SBG-7 (age = 240.9 Ma relative to MMhb-1 (519.5 Ma) [*Alexander et al.*, 1978]). The samples were heated in a molybdenum crucible using radio frequency induction within an ultrahigh vacuum system on a line to a Nuclide model 6-60-SGA mass spectrometer. Samples were analyzed by the incremental heating technique in which the sample is heated repeatedly at successively higher temperatures. Results are presented as release spectra in which the horizontal width of each box represents the size of an increment relative to the others, and the height represents the uncertainty associated with each apparent age. Plateau ages (designated as Tp) were calculated from consecutive gas increments that together constitute >50% of the total gas released. A 95% confidence limit using only the analytical uncertainty was the basis for determining whether consecutive increments overlapped in age. Age uncertainties were calculated by the method described by *Dalrymple et al.* [1981], are reported at the 2σ level, and include the uncertainty in the flux measurement (J value). Analytical results for each sample are given in the Appendix[1].

5. Results

Fourteen muscovite and 12 biotite separates were dated in this study, including 24 mica separates from the metasedimentary

[1]Supporting data are available with entire article on microfiche. Order by mail from AGU, 2000 Florida Ave., NW, Washington, DC 20009 or by phone at 800-966-2481; $2.50. Document 97TC01629M. Payment must accompany order.

rocks which surround the HPG and 2 muscovite separates from the granite itself. Spectra were obtained from 6 mica pairs of schist and metagraywacke. The release spectra of all 26 mica separates are shown in Figure 3. In Figure 3, and in the text following, the sample number for the metasedimentary units is preceded by letters which represent the metamorphic grade of the sample (GZ, garnet zone; ST, staurolite zone; S, sillimanite zone; and KY, kyanite zone). Plateau and near-plateau dates are interpreted to record cooling through closure interval temperatures required for ^{40}Ar retention. It has long been recognized that cooling rate markedly affects the integrated closure temperature [*Dodson*, 1973]. Although the nominal closure temperature for Ar diffusion in muscovite is often cited as ca. 350°C [*McDougall and Harrison*, 1988], studies in slowly cooled terranes have calculated integrated closure temperatures as low as ~295°C and rim closure temperatures of ~205°C [*Hodges et al.*, 1994]. In light of the evidence for slow cooling presented below, we assume integrated mica (muscovite and biotite) closure temperatures in the range of 250°-300°C.

Although less than half of the total samples dated yield strict plateaus (Figure 3), we note that most of the samples are well behaved in that they yield young age increments only for the first 5-10% of the gas released and then level off to form near plateaus. Also, there is the same amount of age variability across the region regardless of whether all the data or only the plateau dates are considered. Because of these points, in the following discussion we interpret essentially all of the data (both total gas and plateau dates) as informative and representative of the regional cooling history.

Dates range from as old as ~1818 Ma to as young as ~1270 Ma with considerable scatter in between. However, most dates fall into one of two age range categories (Figure 4). For instance, 12 country rock mica separates yield relatively old dates (1600-1655 Ma), whereas seven separates (granite and country rock) yield dates between 1440 Ma and 1510 Ma. For a given mineral, there is no relation between age and physical grain size. For example, biotites from samples ST-42 and ST-87 have essentially the same physical grain size but have a nearly 200 Ma age discordance. Also, biotite from sample ST-88 is coarser than biotite from ST-87 (located only 2 km away) but yields a date which is about 50 Ma younger. One biotite separate obtained from schist collected just northeast of the HPG (ST-18) yielded an apparent age of 1818±12 Ma. Abundant geothermometric data indicate that these rocks were heated to temperatures above 550°C when the ~1710 Ma HPG intruded [*Helms and Labotka*, 1991; *Friberg et al.*, 1996]. This fact, together with the fact that surrounding muscovite dates are all 1400-1500 Ma (samples HPG-1, HPG-5, GZ-11, and GZ-15), indicates that the 1818 Ma date is unrealistically old and probably affected by excess ^{40}Ar. Finally, for a given mineral there is no relation between age and presence or absence of late porphyroblasts, in part because these porphyroblasts constitute only a small modal percentage of the muscovite or biotite populations dated.

5.1. Early Proterozoic (1600-1655 Ma) dates

Six muscovite and 6 biotite separates from the southern Black Hills yielded Early Proterozoic $^{40}Ar/^{39}Ar$ dates between 1600 and 1655 Ma (Figure 3). Most of these dates were obtained from samples located between the two domal regions and also south of the Bear Mountain dome (Figure 2). Two samples (ST-107 and ST-112) yielded concordant mica pair dates suggesting cooling of these rocks through the average mica closure interval between 1620 and 1640 Ma. Three other samples (S-107, ST-87, and ST-47) yielded biotite dates somewhat older than those of coexisting muscovite. We surmise that the reverse age discordance exhibited by these mica pairs probably reflects incorporation of relatively small amounts of unresolved excess ^{40}Ar. Preferential intake of excess ^{40}Ar into biotite over coexisting muscovite is well known [*Brewer*, 1969] and appears to be related to the existence of weaker K-O bonds in biotite relative to muscovite [*Dahl*, 1996].

5.2. Middle Proterozoic dates

Six muscovite and 5 biotite separates obtained from 10 samples of the metasedimentary rocks collected in the domal regions yielded Middle Proterozoic $^{40}Ar/^{39}Ar$ dates between 1270 and ~1560 Ma (Figure 2). Two dates were also obtained from samples of the HPG collected near Harney Peak. Muscovite from a coarse-grained sample (HPG-1) yielded a plateau date of 1403±8 Ma. Approximately 3 km to the east-southeast, muscovite books from a pegmatitic phase of the granite yielded a somewhat discordant age spectrum with a total-gas date of 1456±34 Ma. The difference in the grain sizes of these samples might be a factor that contributed to the difference in their dates and style of release patterns.

6. Discussion

We have obtained 26 dates for minerals from 20 different rock samples collected over much of the southern Black Hills. There is a general pattern of relatively old, Early Proterozoic (>1600 Ma) dates existing between the two domal regions and south of Bear Mountain dome (Figure 2), although there is considerable scatter in the age data (Figure 4). We have acknowledged the likely presence of some excess ^{40}Ar in the older population but do not consider it probable that the entire older population is the result of swamping by excess ^{40}Ar and therefore meaningless. The spectra are, for the most part, well behaved from both muscovite and biotite separates, and the dates obtained are geologically reasonable. We interpret the 1600-1655 Ma dates as representing the time of initial cooling of these rocks through average Ar mica retention conditions. These dates are over 50-100 m.y. younger than the ~1710 Ma HPG and therefore are too young to reflect simple cooling following a heating event at 1710 Ma [*Carslaw and Jaeger*, 1959]. If the country rock into which the granite intruded was cold (i.e., <300°C), then the thermal perturbation of the geotherm created by the intrusion would dissipate quickly and the reset mica ages should be close (within 10-20 m.y.) to the age of the intrusion.

Instead, ambient country rock temperatures at the time of granite intrusion must have been above conditions sufficient for diffusive loss of ^{40}Ar over geologic timescales (i.e., above ~250°-350°C), and we associate the cooling of these rocks at 1655-1600 Ma to postintrusion regional uplift. Because of the similar average retention temperatures for muscovite and biotite, we are unable to ascertain with certainty whether this period of uplift was rapid or slow. Similar plateau and total gas dates from coexisting muscovite and biotite (i.e., in samples ST-107 and ST-112) using the incremental heating method do not necessarily imply rapid cooling [see *Hodges et al.*, 1994]. In fact, the ~50

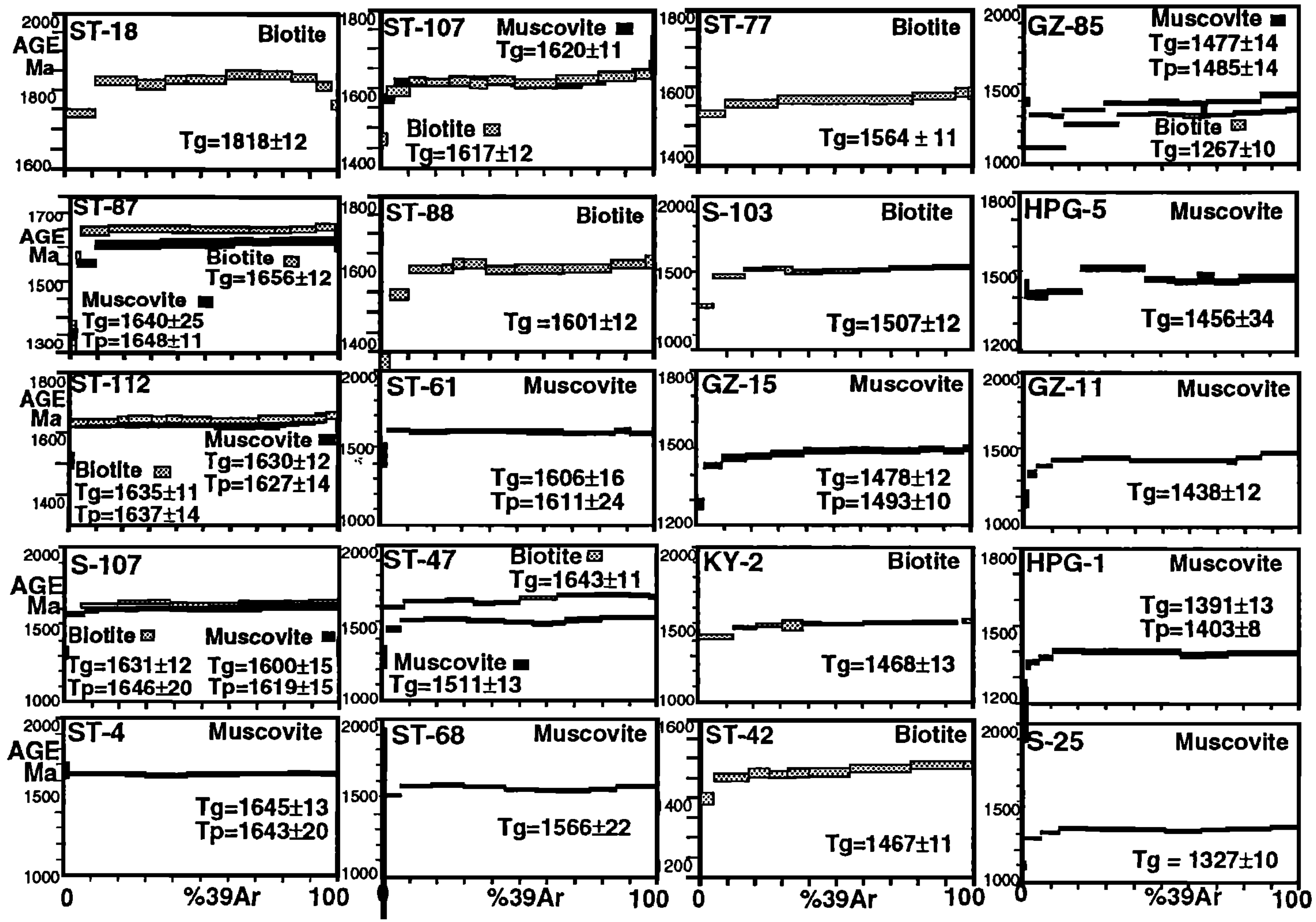

Figure 3. $^{40}Ar/^{39}Ar$ mica age spectra from the southern Black Hills. Tg represents total gas age; Tp represents plateau age. Prefixes to sample numbers represent metamorphic grade. GZ is garnet zone, ST is staurolite zone, S is sillimanite zone, and KY is kyanite zone. See text for discussion.

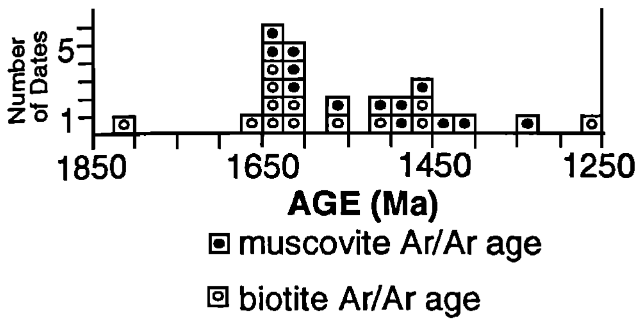

Figure 4. Summary histogram of mean $^{40}Ar/^{39}Ar$ mica age data from the southern Black Hills. Early Proterozoic dates are on the left and Middle Proterozoic dates are on the right.

m.y. range in mica cooling ages suggests that it was probably not rapid; rapid cooling of a region should result in uniform ages from different localities [*Holm and Lux*, 1996]. In addition, preliminary investigations suggest that within this older population mica age may vary with composition (e.g., with Mg/(Fe+Mg) in biotite and K/(Na+K) in muscovite). If real, this would further indicate that cooling and uplift were slow during this time period as composition-controlled age variations would only be detected in slowly cooled terranes [*Dahl*, 1996].

As noted earlier, petrographic analysis of some of the metasedimentary rocks we dated (samples ST-107, ST-112, and S-107) reveals two generations of muscovite, one in the primary (S2) foliation and one occurring as coarser, late, randomly oriented porphyroblasts. The late muscovite widely recognized in the southern Black Hills is commonly interpreted to represent growth of that mineral during the low-P, high-T metamorphism associated with intrusion of the HPG. However, *Berry et al.* [1994] have proposed recently that at least some new growth of muscovite occurred during a younger, low-temperature thermal event below the biotite closure temperature. In this study, muscovite and biotite dates from rock samples containing late muscovite porphyroblasts are analytically identical, and there is no constraint to suggest that late muscovite grew below the biotite closure temperature. Our results therefore are consistent with the common interpretation of late muscovite growth being related to intrusion of the HPG.

Mica $^{40}Ar/^{39}Ar$ dates from the domal regions, from both undeformed samples of the HPG and from the metasedimentary country rock, are consistently Middle Proterozoic. They are similar to muscovite $^{40}Ar/^{39}Ar$ dates obtained by *Berry et al.* [1994] from country rock collected northeast of the granite. Except for sample ST-47, our data give Middle Proterozoic dates for both biotite and muscovite. An important question is whether these younger dates are the result of a superposed thermal resetting event or whether they reflect the time of initial cooling of these rocks during uplift or slow isobaric relaxation of the geotherm.

It is well known that voluminous Middle Proterozoic (1500-1300 Ma), midcrustal plutons were emplaced along a northeast trending transcontinental belt extending from southern California to Labrador [*Anderson*, 1983]. We suggest, however, that our Middle Proterozoic mica ages are probably not the result of a pluton-related thermal resetting event considering that the Black Hills are located over 200 km north of any identified Middle Proterozoic plutons (Figure 1). Admittedly, there are no basement exposures for a considerable distance south of the Black Hills, and it is possible that Middle Proterozoic plutons might extend close to the Black Hills given their apparent preference for intruding into Proterozoic crust (Figure 1). However, if our Middle Proterozoic dates from the domal regions (and similar dates from the northern Black Hills [*Gardner et al.*, 1996]) were interpreted to represent a widespread thermal resetting event, it would be difficult to explain why rocks located between the domal regions and also south of Bear Mountain dome were selectively not reset. In addition, Early Proterozoic crust invaded by Middle Proterozoic plutons in the southwestern United States yields hornblende $^{40}Ar/^{39}Ar$ dates of 1430-1350 Ma indicating Middle Proterozoic regional metamorphism [i.e., *Karlstrom et al.*, 1997]. The lack of any Middle Proterozoic hornblende dates from the Black Hills [*Berry et al.*, 1994; *Dahl et al.*, 1996] might therefore be considered consistent with the lack of evidence for Middle Proterozoic plutonism in the area.

We believe the younger Middle Proterozoic mica dates may be best interpreted as evidence of slow isobaric cooling related to relaxation of an elevated geotherm or as evidence of a period of slow Middle Proterozoic (1500-1300 Ma) uplift. The regional pattern of 1400 to 1600 Ma Rb-Sr and K-Ar biotite ages from rocks in the southern third of the Wyoming Province have long been interpreted to reflect Middle Proterozoic uplift [*Peterman and Hildreth*, 1978; *Karlstrom and Houston*, 1984]. Thermochronologic data from provinces farther southwest in Arizona indicate that terrane assembly at 1700 Ma was followed by a >200 m.y. stable period of little to no uplift [*Karlstrom and Bowring*, 1993]. This stable period was then followed by slow, regional uplift beginning at about 1450 Ma and continuing for at least several hundred million years [*Bowring and Karlstrom*, 1990; *Karlstrom and Bowring*, 1993]. Indeed, the timing of intrusion and cooling proposed here for the HPG is remarkably comparable to the cooling history recently proposed for the ~1700 Ma Crazy Basin pluton of central Arizona. Substantial Middle Proterozoic age gradients have been obtained from Crazy Basin pluton muscovite crystals using both laser spot-fusion mapping (~400 m.y. core-to-rim age variations [*Hodges et al.*, 1994]) and furnace step heating [*Heizler and Ralser*, 1996]. The 100-200 m.y. age gradients commonly exhibited by our Middle Proterozoic mica spectra (Figure 3) and the ~200 m.y. spread in Middle Proterozoic dates are together strong evidence for slow cooling.

7. Interpretations of Map View Age Patterns

7.1. Retention Variation

We have noted above the possibility that the age scatter within the older population might reflect composition-controlled variations in Ar retention intervals, and we wonder if the overall map view age pattern seen in Figure 2 might also reflect variation in retention intervals on a larger scale. Actual closure temperature intervals of minerals are influenced by factors such as effective diffusion dimension (physical grain size?), mineral composition, and cooling rate. The apparent lack of correlation between age and physical grain size noted above leads us to speculate that subgrain domains (bounded by dislocations, cleavages, alteration phases, etc.) variably governed effective diffusion dimension (and thus relative cooling age) among our

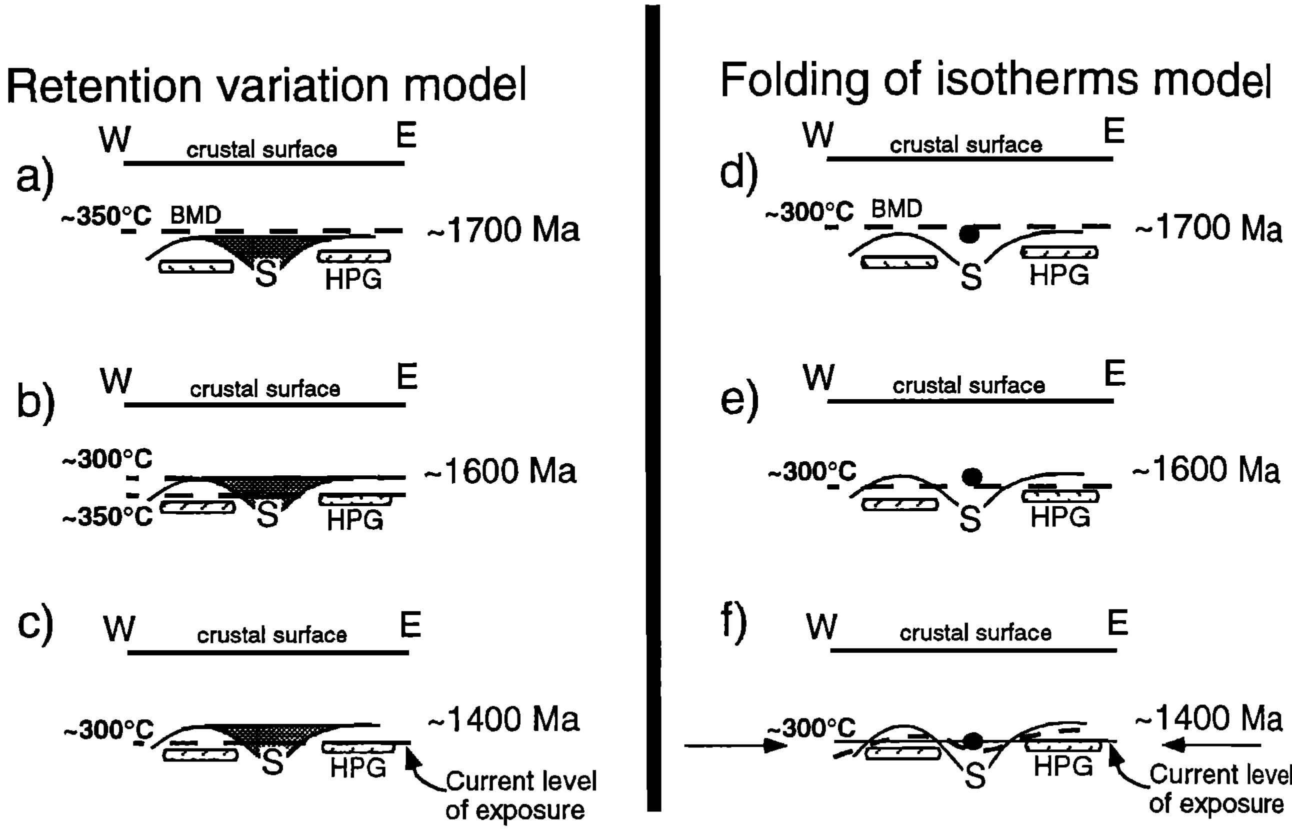

Figure 5. Simple schematic cross-sectional (upper crust only) synopses depicting two end-member interpretations for the mica age pattern preserved in the southern Black Hills. Both models begin at ~1700 Ma shortly after the intrusion of the Harney Peak Granite (HPG) which caused doming of the surrounding rock (creating a synform between the domes, S). In the retention variation model (left), long-term midcrustal residence and very slow cooling (associated with either downward motion of horizontal isotherms or very slow subhorizontal uplift of the region) occurs for several hundreds of million years after intrusion of the HPG. The different cooling ages result from differences in Ar retention intervals between the synform (S) region (shaded) and domal regions, not differences in structural depth. (a) At ~1700 Ma, all micas are above their retention intervals in the midcrust. (b) By ~1600 Ma, slow cooling is recorded in the more highly retentive mica minerals of the synform region. (c) At ~1400 Ma, micas from the domal regions cool below their retention intervals. In the folding of isotherms model (right), the different low-temperature (350°-300°C) histories for rocks within and without the synform (S) are interpreted to be the result of broad Middle Proterozoic folding after a period of protracted thermal equilibration in the middle crust following HPG intrusion. Currently exposed rocks within the synform are denoted with a solid circle. (d) Intrusion of the ~1710 Ma Harney Peak Granite into deformed country rock with ambient temperatures somewhat above 350°C. (e) Minor uplift during the next 100 m.y. results in minor slow cooling of the rocks currently exposed in the synform. (f) Approximately east-west oriented compression beginning at ~1500 Ma results in reactivation and accentuation of the synform and folding of the 1500 Ma ~300°C isotherm. This folding results in uplift and cooling of the rocks outside of the synform and juxtaposition of relatively cold rocks within the synform. BMD is Bear Mountain dome.

micas. A retention-composition relationship is suggested within our data set by the fact that relatively old biotites and muscovites from the synform (Figure 2) are also enriched in Mg/(Fe + Mg) and depleted in K/(Na + K), respectively, relative to micas in the domal regions [*Dahl et al.*, 1993]. Such a correlation appears broadly consistent with crystal-chemical predictions [*Dahl*, 1996].

Isolating the potential contributions of microstructure and composition on Ar retention in our micas is an exceedingly difficult task which can only be approached through outcrop-scale dating studies designed to eliminate the regional variable of uplift/cooling history. Full treatment of this matter is currently underway but beyond the scope of this paper. For now, we acknowledge that the synform region exhibits differences in lithology, mica composition, and possibly effective diffusion dimension in micas distinct from the surrounding domal regions. Given these differences, the age pattern might then be the result of slow subhorizontal uplift and cooling of minerals with different Ar retention intervals (i.e., higher retention intervals within the synform region and south of Bear Mountain dome). This explanation for the Early and Middle Proterozoic mica age pattern is depicted on the left side of Figure 5 (retention variation model). Immediately after intrusion of the HPG, all rocks currently exposed in the southern Black Hills are at ambient temperatures slightly above ~350°C (the nominal closure temperature of muscovite, Figure 5a). By ~1600 Ma, the crust has cooled uniformally (as shown by the deepening of horizontal isotherms). Synform rocks with their higher Ar retention interval (say ~350°C) would have closed to diffusion of Ar by this time, whereas domal rocks with lower Ar retention intervals (say ~300°C) remained open to Ar diffusion (Figure 5b). Slow cooling continues for about 200 m.y. until at ~1400 Ma the current level of exposure of the domal regions cools below ~300°C (Figure 5c).

7.2. Folding of Isotherms

If we assume that micas in the southern Black Hills all have essentially similar retention intervals, then the map view age pattern might be interpreted to be the result of broad Middle Proterozoic folding after a period of protracted thermal equilibration in the middle crust following HPG intrusion. In this scenario, we interpret the older mica dates preserved between the domal regions and south of Bear Mountain as representing shallower crustal regions which had already cooled prior to renewed Middle Proterozoic uplift (Figures 5d and 5e). The current preservation of older mica dates between the domes could reflect reactivation of a preexisting Early Proterozoic fault-bounded synformal structure (and down warping of relatively cold rocks) during a period of approximately east-west-oriented contraction and slow uplift during the Middle Proterozoic (Figure 5f). To the south of the domes where dates are older in the west and where the synform structure is absent, the same isotherm might be only broadly warped and dip gently to the west. The fact that the map pattern of young-to-old-to-young mica ages coincides with a preexisting mapped Early Proterozoic synform [*DeWitt et al.*, 1989] could be taken as strong evidence that the structure was reactivated during the Middle Proterozoic.

We emphasize that this interpretation for the age pattern does not require major crustal deformation or large amounts of differential displacement along the synform bounding faults during the Middle Proterozoic (Figure 5f). We also note that the synform bounding faults [*DeWitt et al.*, 1989] between the domal regions crosscut only Early Proterozoic metamorphic rocks. Other than this simple crosscutting relation, there are no field constraints indicating that these faults could not have been reactivated at some later time. Indeed, without information such as the thermochronologic data presented here, it is nearly impossible to ascertain the timing of motion on these faults from field data alone.

Historically, the Middle Proterozoic era in North America has been interpreted as a period of profuse anorogenic plutonism associated with extension [*Windley*, 1993]. We have raised the enticing interpretation that the cooling age pattern in the southern Black Hills might reflect Middle Proterozoic midcrustal shortening. Although it remains to be shown whether this interpretation (or the alternative retention variation model) is correct, it is at least consistent with several recent studies from the southwestern United States which provide evidence for a widespread midcrustal contractile deformational event during the Middle Proterozoic [*Nyman et al.*, 1994; *Duebendorfer and Christensen*, 1995; *Kirby et al.*, 1995; *Gonzales et al.*, 1996]. If ultimately verified, then the region affected by the compression may be substantially larger than originally proposed [see also *Fueten and Redmond*, 1997].

8. Implications for the Early Proterozoic

8.1 Early Proterozoic Geothermal Gradient

The mica $^{40}Ar/^{39}Ar$ dates obtained here indicate that the HPG did not cool through the muscovite Ar retention interval until 200-300 m.y. after intrusion. Thus ambient country rock temperatures at the depth and time of intrusion of the HPG were warmer than ~300°-350°C. Abundant geothermometric data indicate that the country rock surrounding the granite was heated by the granite to temperatures above 550°C [*Friberg et al.*, 1996]. However, countryrock hornblende $^{40}Ar/^{39}Ar$ ages are concordant (within error) with the pluton age [*Berry et al.*, 1994; *Dahl and Holm*, 1996; *Dahl et al.*, 1996]. This indicates that after the pluton-related heating event, the country rocks cooled quickly to temperatures below 500°C (the closure temperature widely assumed for hornblende), suggesting that the ambient temperature of 3-4 kbar country rocks prior to intrusion of the granite was below 500°C. Garnet rim temperatures of 530°-550°C associated with HPG intrusion [*Helms and Labotka*, 1991; *Friberg et al.*, 1996] in the country rock surrounding the granite have been interpreted by some [e.g., *Nabelek et al.*, 1992a] as indicating the ambient temperature at the level of granite emplacement (3-4 kbar). However, we emphasize that these rim temperatures are associated with heating of the country rock by the pluton (which perturbed the ambient geothermal gradient) and therefore cannot be used as an estimate of the ambient geothermal gradient at (or just prior to) the time of HPG emplacement.

Taken together, the hornblende and mica age data from the southern Black Hills indicate that the country rock temperature was between 350°C and 500°C at the 12-14 km depth of emplacement of the HPG, suggesting an average, upper crustal, geothermal gradient of 25°-40°C/km just prior to intrusion. This determination is somewhat lower than the 40°-45°C/km geothermal gradient estimated by *Nabelek et al.* [1992a] on the basis of oxygen isotope data. We conclude that the average geothermal gradient in the southern Black Hills was not abnormally high just prior to granite intrusion and that the lower crustal anatexis (which resulted in the HPG magma) was the result of a temporary tectonic perturbation of an average geotherm.

8.2. Early Proterozoic P-T Evolution

As described above, peak country rock metamorphic pressures of 5-6.5 kbar in the southern Black Hills contrast with final equilibration pressures of 3-4 kbar [*Terry and Friberg*, 1990; *Helms and Labotka*, 1991; *Terry et al.*, 1994]. The peak metamorphic pressures have been interpreted by some as representing the initial conditions of emplacement of the adjacent HPG. For instance, *Terry et al.* [1994] envision HPG emplacement (beginning at depths >22 km) as concomitant with significant structural doming and regional uplift to final emplacement depths of 12-14 km. We note that to our knowledge no timing constraints exist which require large amounts (>8-10 km or more) of uplift and doming to have occurred together with intrusion. In addition, we disagree with this interpretation for two reasons. First, in section 8.1 we noted that the 3-4 kbar country rocks now exposed at the surface were probably cooler than ~500°C prior to granite intrusion; ambient temperatures this low would not have been likely at ~22 km. Second, the existence of prograde, low-P, metamorphic isograds (staurolite+biotite, andalusite+biotite, and sillimanite) surrounding the HPG [*Helms and Labotka*, 1991] also suggest that the country rock must have been relatively cold (~350°-500°C) when the granite was emplaced. A simple uplift/cooling P-T path from peak (>22 km) to garnet-rim (12-14 km) pressures solely during granite intrusion would not allow for the development of such low-P, prograde metamorphic isograds.

8.3. Proposed Proterozoic P-T Paths

In Figure 6, we reconstruct two separate P-T paths for rocks of the southern Black Hills: one for low-P metamorphic rocks surrounding the HPG east of the synform and one for medium-P kyanite bearing rocks of the Bear Mountain dome west of the synform (Figure 2). Tectonic burial of Early Proterozoic rift sediments as young as ~1880 Ma indicates crustal thickening and heating post-1880 Ma. Results of recent garnet and staurolite Pb-Pb step-leach dating of Bear Mountain dome rocks suggests the collision and attendant peak metamorphism occurred at about 1760 Ma [*Dahl and Frei*, 1997]. At that time, paleopressures were at or above 6.5 kbar in the Bear Mountain dome and 4.5-5 kbar in the Harney Peak dome (Figure 6). Abundant barometric data from garnet rims throughout the southern Black Hills indicate emplacement of the HPG at 3-4 kbar [*Helms and Labotka*, 1991]. While it is well documented that some doming and uplift occurred with emplacement of the HPG [*Redden et al.*, 1985], for the above reasons we consider it unlikely to have been of the order of 8-10 km or more. We propose instead that most of the uplift of the country rock from 20-25 km depths (or more) occurred prior to emplacement of the HPG at 12-14 km depths. In this scenario (Figure 6), the HPG intruded relatively cold rocks in the southern Black Hills, imposed the prograde thermal isograds surrounding it (Figure 2), and cooled quickly to ambient country rock temperatures (Figure 6). The HPG stabilized and resided in the midcrust where it cooled slowly for several hundreds of million years. We note that the P-T paths proposed here are very similar in character to the looping P-T paths proposed for Proterozoic midcrustal rocks of the southwestern United States [*Williams and Karlstrom*, 1996].

8.4. Speculations on the Origin of the Harney Peak Magma

The thermochronologic data presented here suggest that after Early Proterozoic collision and intrusion of the HPG the area of the southern Black Hills did not undergo rapid uplift. Instead, intrusion was followed by a prolonged period of tectonic quiescence and midcrustal residence from ~1700 to 1500 Ma during which probably no or perhaps only minor slow uplift occurred. We propose therefore that the HPG magma was emplaced into isostatically stable crust of relatively normal thickness. Since rifting occurred prior to collision in the Black Hills, the subsequent collision of thinned crust may have resulted in only moderately thick crust [cf. *Bowring and Karlstrom*, 1990].

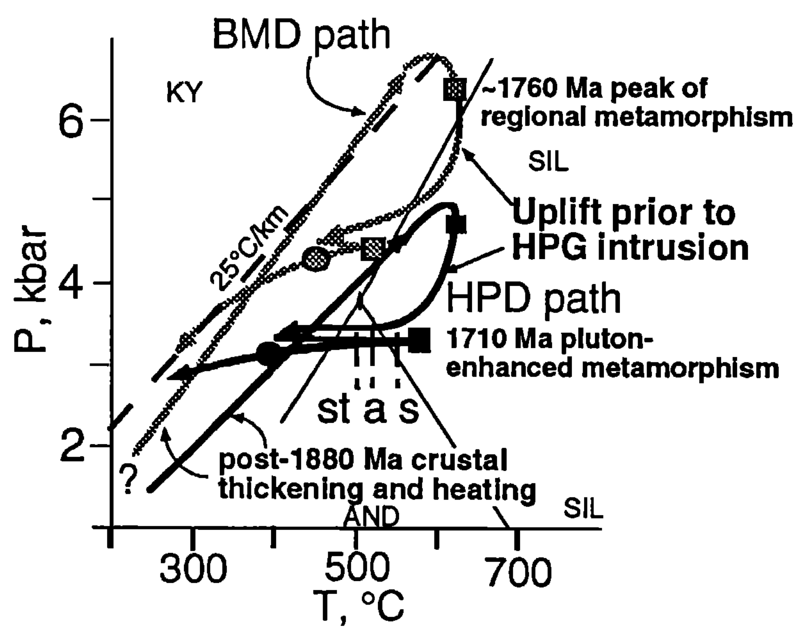

Figure 6. Proposed pressure-temperature-time paths for medium-pressure and low-pressure Early Proterozoic metasedimentary rocks in the southern Black Hills, South Dakota. Aluminosilicate triple point is after *Holdaway* [1971]. Abbreviations st, a, and s represent staurolite+biotite, andalusite+biotite, and sillimanite isograds, respectively. BMD is Bear Mountain dome; HPD is Harney Peak dome. Solid squares represent peak metamorphic conditions (after *Terry et al.* [1994] for BMD and *Terry* [1990] for HPD) and garnet-rim thermobarometric data (after *Helms and Labotka*, [1991]). Solid circles represent a ~200 m.y. period of tectonic quiescence and stability after emplacement of the ~1710 Ma Harney Peak Granite. Slow cooling through ~300°C occurred at 1500-1300 Ma for both paths. See text for further explanation.

Table 1. Interpretation of the 1880-1400 Ma Geologic History of the Black Hills, South Dakota

Event	Absolute age, Ma	Reference
Rifting	~1880	*Redden et al.* [1990]
Thrusting and nappe folding (S_1)	<1800	*Dahl* [1993]
Isoclinal folding (S_2) and metamorphism	1740-1760	*Dahl et al.* [1996] *Dahl and Frei* [1997]
Subcrustal lithospheric thinning/crustal uplift	just prior to 1710 (?)	This study
Doming and intrusion of the Harney Peak Granite with formation of S_3 and late muscovite overgrowths	~1710	*Redden et al.* [1990]
Tectonic quiescence with minor uplift; weak S_4 foliation may have formed during this time	1710-1500	This study *Redden et al.* [1990]
Slow midcrustal cooling possibly associated with contraction	~1400	This study

Given this, the 8-10 km of uplift which we propose above to have preceded HPG intrusion may have been enough to return the moderately thick crust to a relatively normal thickness prior to emplacement of the HPG.

The generation of the HPG magma is commonly attributed to partial melting of the lower crust in response to extreme crustal thickening and thermal relaxation [*Helms and Labotka*, 1991; *Nabelek et al.*, 1992a, b]. However, the lack of substantial rapid postintrusion uplift suggests isostatically stable crust of relatively normal thickness [cf. *Karlstrom and Bowring*, 1993]. As an alternative possibility, *Sims et al.* [1991] have proposed that the HPG might be related to the suturing of the rocks of the Central Plains Orogen along the Cheyenne Belt. While this hypothesis eliminates the need for partial melting of an overthickened crust, it is inconsistent with both the timing and the well-documented southward dip of the Cheyenne suture [*Duebendorfer and Houston*, 1987].

As noted in the geologic setting above, in the whole of the Black Hills the HPG is spatially associated with the deepest exposed Early Proterozoic country rock. Mica cooling ages in the northern Black Hills [*Gardner et al.*, 1996] are comparable to the southern Black Hills, and therefore the spatial association does not appear to be related to greater uplift of the southern region during or since the Middle Proterozoic. We have established in this paper that Early Proterozoic postcollisional uplift and cooling of the country rock occurred prior to midcrustal 3-4 kbar granite emplacement, and therefore this spatial association is not related to in situ biotite dehydration melting of the deepest exposed portion of the orogen. Although the timing of Early Proterozoic unroofing from ~6 kbar pressures to 3-4 kbar pressures is uncertain, we speculate that this uplift, and the generation and emplacement of granite which followed it, are genetically linked, and both may have been initiated by a deeper-seated process perhaps associated with subcrustal lithospheric thinning (i.e., mantle delamination). One consequence of delamination is isostatic uplift and thinning of the overlying crust. A second consequence is an increase in mantle heat flux across the Moho (by shallowing of the asthenosphere-lithosphere boundary) and lower crustal melting [*Kay and Kay*, 1993]. Given an appropriate time lag between these two responses, delamination might provide an explanation for why cooling of upper crustal rocks is followed by fusion of the lower crust and melt emplacement into stable midcrustal rock. Postcollisional mantle delamination has been proposed on the basis of geophysical evidence for portions of the Trans-Hudson orogen to the north (central Saskatchewan, Canada) where postcollisional magmas exist [*Baird et al.*, 1995] and has been suggested as a possible cause for genesis of postcollisional granites in the Early Proterozoic Penokean orogen of the southern Lake Superior region (Figure 1) [*Holm and Lux*, 1996]. Whatever the mechanism for posttectonic granite genesis, whether by delamination or thermal relaxation [*Windley*, 1993], as with younger collisional belts, we envision crustal thickening followed by crustal thinning with generation and emplacement of late-collisional or anatectic granite to be intimately related [e.g., *Burchfiel et al.*, 1992; *Molnar and Lyon-Caen*, 1988; *Turner et al.*, 1992].

9. Summary and Conclusions

The mica $^{40}Ar/^{39}Ar$ age data from the southern Black Hills depict a simple map view pattern in which relatively old dates (1600-1655 Ma) are preserved within the synform structure located between the Harney Peak and Bear Mountain domes and also south of Bear Mountain. In contrast, Middle Proterozoic mica dates (~1500-1270 Ma) are obtained from the surrounding domal regions. The data are interpreted to indicate a period of low-temperature cooling associated with either slow Middle Proterozoic isobaric cooling or uplift at ~1300-1500 Ma. The map view age pattern may reflect essentially horizontal slow cooling of an area which exhibits variations in mica Ar retention intervals. The pattern may alternatively be explained as reflecting a mildly folded Middle Proterozoic (~1500 Ma) ~300°C isotherm. If so, shortening may have been localized along a major preexisting north-south oriented synformal structure and is consistent with a regional Middle Proterozoic west-to-northwest contractile event recently proposed for western North America [*Nyman et al.*, 1994].

In addition to providing evidence for slow Middle Proterozoic cooling, the mica age data provide important implications for the Early Proterozoic tectonothermal history of the southern Black Hills (Table 1). These include the following: (1) Intrusion of the HPG was followed by a prolonged period (~200 m.y.) of crustal stability and tectonic quiescence, 2) The HPG magma intruded into crust of relatively normal thickness, 3) Prior to intrusion, crust overthickened during collision (after ~1880 Ma) was thinned during a period of uplift, 4) Last, we speculate that Early Proterozoic uplift and crustal thinning and subsequent generation of the HPG magma may have been the result of localized thinning of the overthickened subcrustal lithosphere beneath the southern Black Hills.

Finally, we note that at ~1710 Ma, the crust in the southern Black Hills was probably not 60-70 km thick as might be inferred if the 12-14 km of crust that originally overlay the HPG were added to the current 45-55 km crustal thickness. Instead, crustal structure has probably been thickened since the Early Proterozoic, either by magmatic underplating during the Middle Proterozoic together with thickening due to shortening and/or possibly even by much younger Laramide tectonism and magmatism.

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