Paleoproterozoic Metamorphism in the Northern Wyoming Province: Implications for the Assembly of Laurentia

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ABSTRACT

U-Pb ages measured on zircons from the Tobacco Root Mountains and monazite from the Highland Mountains indicate that the northwestern Wyoming province experienced an episode of high-grade metamorphism at ~1.77 Ga. Leucosome emplaced in Archean gneisses from the Tobacco Root Mountains contains a distinctive population of zircons with an age of 1.77 Ga but also contains zircons to ~3.5 Ga; it is interpreted to have been derived primarily by anatexis of nearby Archean schist. A granulite facies mafic dike that cuts across Archean gneissic banding in the Tobacco Root Mountains contains two distinct populations of zircons. A group of small (<50 μm) nonprismatic grains is interpreted to be metamorphic and yields an age of 1.76 Ga; a group of slightly larger prismatic grains yields an age of 2.06 Ga, which is interpreted to be the time of crystallization of the dike. Monazite from a leucogranite from the Highland Mountains yields a well-defined age of 1.77 Ga, which is interpreted as the time of partial melting and emplacement of the leucogranite. These results suggest that the northwestern Wyoming province, which largely lies within the western part of the Great Falls tectonic zone, experienced a metamorphic maximum at 1.77 Ga. This age is ~100 m.yr. younger than the proposed time of Wyoming-Hearne collision in the central Great Falls tectonic zone (1.86 Ga) and suggests that the northwestern Wyoming province may have been involved in a separate, younger collisional event at ~1.77 Ga. An event at this time is essentially coeval with collisions proposed for the eastern and southeastern margins of the province and suggests a multiepisodic model for the incorporation of the Wyoming craton into Laurentia.

Online enhancement: appendix.

Introduction

The Great Falls tectonic zone (GFTZ) is a zone of high-angle faults and lineaments lying between the Wyoming and Hearne cratons. It was originally proposed as a Paleoproterozoic feature that marks the northern boundary of the Wyoming province (O'Neill and Lopez 1985; fig. 1). It contains both juvenile Paleoproterozoic rocks and overprinted Archean basement of the Montana metasedimentary terrane of the northern Wyoming province (e.g., Mogk et al. 1992; Mueller et al. 2002, 2004). At present, however, there is no consensus concerning the nature of the tectonic environment in which it formed (collisional, transpressional, or transform) or the time at which it formed (Archean or Proterozoic; O'Neill and Lopez 1985; Hoffman 1988; Boerner et al. 1998; O'Neill 1998; Dahl et al. 1999; Lemieux et al. 2000; Gorman et al. 2002; Mueller et al. 2002). This uncertainty derives in part from the fact that Paleoproterozoic rocks have been documented in only one location within the zone (1.86-Ga rocks of the Little Belt Mountains; Mueller et al. 2002) and in part from thermochronometric data that reveal significant dispersion of

NORTHERN WYOMING PROVINCE

Figure 1.   Generalized geologic map of the northern Wyoming province showing sample locations

Proterozoic mineral ages from Archean rocks of the Montana metasedimentary terrane. These Archean rocks (2.8–3.5 Ga) are relatively widespread in the western part of the GFTZ (e.g., O'Neill and Lopez 1985; Mogk et al. 1992; fig. 1) and commonly yield mineral ages between 1.6 and 1.9 Ga (e.g., K-Ar and Ar-Ar in biotite and hornblende; Hayden and Wehrenberg 1959; Giletti 1971; O'Neill et al. 1988; Erslev and Sutter 1990; Harlan et al. 1996; Brady et al. 1998, 2004b; Roberts et al. 2002).

In contrast, geochronologic and thermochronologic data from Archean and Proterozoic rocks along the southeastern and eastern margins of the Wyoming province have been interpreted in terms of temporally well-constrained Paleoproterozoic collisional orogenesis. For example, the Cheyenne

belt has been proposed to result from the juxtaposition of the Proterozoic Colorado province and the Wyoming craton at about 1.74–1.78 Ga (e.g., Karlstrom and Houston 1984; Chamberlain 1998), and Dahl et al. (1999) interpreted evidence from the Black Hills (South Dakota) to indicate the collision of the Archean Wyoming and Superior cratons at about 1.76–1.71 Ga. Hill and Bickford (2001), however, argue that the Cheyenne belt originally formed as a boundary between Trans-Hudson and Archean crust and marks the northern limit of post-1.80-Ga rifting and bimodal volcanism.

In this article, we present Paleoproterozoic ages derived from U-Pb isotopic analyses of zircons (via sensitive high-resolution ion microprobe reverse geometry [SHRIMP RG]) and monazite (via ID-

Figure 2. Photograph of metamorphosed mafic dike cutting across leucosome-bearing Archean gneisses in the Tobacco Root Mountains.

TIMS [isotope dilution–thermal ionization mass spectrometry]) that formed at 1.77 Ga in Archean rocks of the Montana metasedimentary terrane. These new ages, together with detailed analyses of the geologic context of these rocks (e.g., Burger 2004; Cheney et al. 2004b; Harms et al. 2004b), provide new constraints on the thermotectonic evolution of the GFTZ and the role of the Wyoming province in the assembly of Laurentia. In particular, these data suggest that if the Cheyenne belt does mark a 1.74–1.78-Ga collision with the Colorado province, it would be simultaneous with collision along the northwestern margin of the Wyoming craton. Coeval collision in these areas can be accommodated by a continuous episode of SW-NE-directed plate convergence that first juxtaposed the Wyoming, Superior, and Hearne provinces before the accretion of Proterozoic and perhaps other Archean arcs and microcontinents.

Samples and Methods

The three samples analyzed for this study are as follows:

1. Zircons were separated from sample JBB-97-14E, which is from an unfoliated quartz-feldspar-rich leucosome that appears to have been derived from immediately adjacent schist (quartz-biotite-sillimanite-garnet) and accumulated in the hinge of an isoclinal fold in Archean gneisses and metasedimentary rocks in the Tobacco Root Mountains (Burger 2004; Mueller et al. 2004).

2. Zircons were separated from sample JBB-97-9A, which is from an approximately 5-m-thick, deformed, metabasaltic dike that exhibits a weak foliation generally parallel to its margins. This dike is one of many similar dikes that cut across the banding of the Archean gneisses (e.g., Reid 1963; Vitaliano 1979a, 1979b; Brady et al. 2004a; fig. 2). The dike is in the granulite facies (garnet + plagioclase + clinopyroxene + hornblende + quartz + ilmenite ± orthopyroxene), and thermobarometric calculations yield pressures of 7–11 kb and temperatures of 600°–730°C (Brady et al. 2004a; Cheney et al. 2004b).

3. Monazite was separated from sample HD-95-2, which is from a leucogranite that intrudes Archean quartzofeldspathic gneisses in the Highland Mountains (O'Neill et al. 1988).

Samples were crushed and zircons and monazite separated by hydraulic, density, and magnetic methods. U-Pb measurements of zircons (BB-97-14E and JBB-97-9A) were made at the USGS-Stanford Microanalytical Center using the SHRIMP
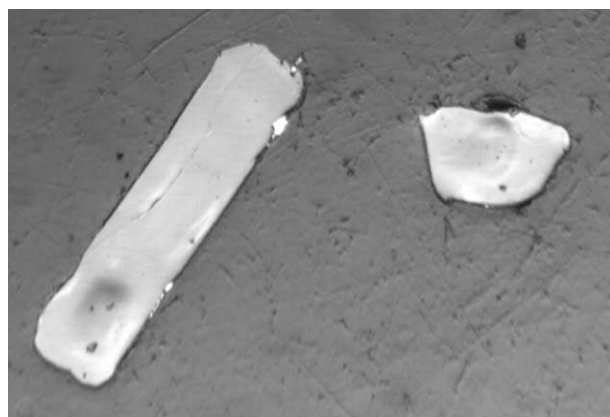
Figure 3. SEM/CL image of zircons from sample JBB-97-9A showing distinct morphologies of 2.06 Ga (acicular) and 1.77 Ga (rounded) grains. Rounded grain is ~50 μm in its longest dimension.

RG ion microprobe (e.g., Compston et al. 1984; Compston and Williams 1992). All grains were imaged prior to analysis (CL [cathodoluminescence] in addition to reflected and transmitted light), and data are reported for "whole" grains only (no data are reported for overgrowths). The multigrain monazite sample from HD-95-2 was analyzed by conventional ID-TIMS methods at the University of Florida (e.g., Krogh 1973; Parrish et al. 1987; Ludwig 2003). All ages are reported with 2σ errors. All chemical and isotopic data discussed in this article are available in the online edition of the *Journal of Geology* and from the *Journal of Geology* office's Data Depository, free of charge upon request.

Results

JBB-97-14E (Leucosome). Twenty zircons were analyzed; they yielded 11 ages between 1.7 and 1.8 Ga and exhibited distinctively low (<0.1) Th/U ratios, which often characterize hydrothermal growth. Ten of the analyses are within 10% of concordia and yield an error-weighted mean $^{207}Pb/^{206}Pb$ age of 1.769 ± 0.006 Ga. The remaining grains exhibited much higher Th/U ratios on average (~6× those of the 1.77-Ga grains; online appendix) and yielded generally discordant ages between 1.9 and 3.5 Ga. These grains are interpreted to originate from the parent schist. The 1.77-Ga date is interpreted to be the time at which the melt crystallized; it provides a likely time for the development of

peak metamorphic temperatures in this area and to mark an episode of Pb loss in the discordant grains.

JBB-97-9A (Metamorphosed Mafic Dike). Two distinct populations of small zircons were recovered and analyzed (fig. 3). Data from 16 of 18 prismatic grains analyzed were <10% discordant and ~2.0 Ga. They yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 2.060 ± 0.006 Ga. Twelve of 13 analyses of the smaller (<50 μm) round grains yielded ages <10% discordant and an error-weighted mean $^{207}Pb/^{206}Pb$ age of 1.763 ± 0.008 Ga. The younger grains exhibit distinctly lower Th/U ratios than those of the prismatic grains (~3× less; online appendix) and are interpreted to have formed during metamorphism.

HD-95-2 (Leucogranite). A homogeneous population of light yellow, irregularly shaped grains of monazite yielded data via ID-TIMS that are ~7% discordant with a $^{207}Pb/^{206}Pb$ age of 1.77 Ga. O'Neill et al. (1988) reported that zircons from this rock yield a mixture of Archean and Proterozoic ages, but they did not provide precise ages for either component. The monazite age reported here is compatible with those conclusions and suggests that the leucogranite formed at ~1.77 Ga, probably via partial melting of Archean gneisses.

Discussion

Tectonic Evolution of the Northern Wyoming Province. Data from the many studies noted above show that Archean rocks of the Montana metasedimentary terrane/GFTZ in southwestern Montana record evidence for reheating and subsequent cooling during the interval 1.6–1.9 Ga. The most accurate estimate for the time of peak metamorphic conditions during this interval is 1.77 Ga, based on the U-Pb zircon and monazite ages presented here. This estimate is supported by U-Th-Pb isotopic data from monazites in the Tobacco Root Mountains (1.72–1.78 Ga; Cheney et al. 2004*a*). For the Tobacco Root Mountains, Cheney et al. (2004*a*, 2004*b*) report that garnets that host some of the monazites exhibit cordierite coronas, which are interpreted as decompression textures. The general coincidence of hornblende ^{40}Ar-^{39}Ar ages with the monazite ages is indicative of rapid uplift and cooling, as would be expected in a collisional orogen (Brady et al. 2004*b*; Cheney et al. 2004*b*).

Although the data reported here and in Cheney et al. (2004*a*) place new, well-constrained limits on Paleoproterozoic thermotectonism in the western GFTZ, their implications for understanding the origin of the GFTZ as a whole are less certain. For
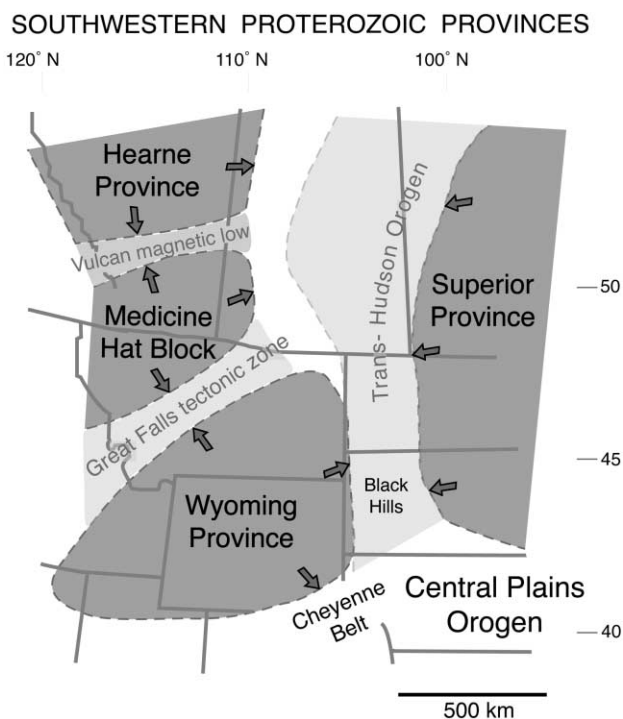
SOUTHWESTERN PROTEROZOIC PROVINCES

Figure 4. Schematic depiction of major cratonic blocks of southwestern Laurentia with arrows depicting margin-normal convergence directions.

example, both the Little Belt and Tobacco Root Mountains contain Archean rocks and lie within the GFTZ (fig. 1). Their geologic histories, however, are quite distinct. In particular, the time of the latest Paleoproterozoic thermal maximum in the western part of the GFTZ (1.77 Ga) is almost 100 m.yr. younger than the time of magmatism and peak metamorphism preserved farther to the east in the Little Belt Mountains (1.86 Ga; Dahl et al. 2000; Mueller et al. 2002; Vogl et al. 2002). It is also important to note that ∼1.77-Ga magmatism in the western part of the GFTZ is limited to the leucogranite reported here. No other magmatism of this age has been reported.

Without accompanying magmatism, the exact nature of the tectonic event associated with the 1.77-Ga metamorphism and its relation to the origin of the GFTZ are difficult to specify (e.g., Foster et al. 2002; Harms et al. 2004a; Mueller et al. 2004). One model that should be considered, however, is collision with a separate terrane (i.e., distinct from the Hearne/Medicine Hat block) that approached the Wyoming margin from a generally southwesterly direction (present coordinates) roughly 100

m.yr. after initiation of the Wyoming-Hearne collision farther to the north (e.g., fig. 5). The paucity of 1.7–1.8-Ga magmatic rocks in southwestern Montana suggests that any significant subduction associated with this collision occurred beneath the approaching plate, or that the event had a significant transpressional component with minimal overall magmatism (e.g., Foster et al. 2002). In either case, convergence along a vector with a generally SW-NE trend is compatible with the orientation of regional-scale fabrics measured in Archean rocks of the Tobacco Root Mountains (Harms et al. 2004b).

The identity of the >1.77-Ga terrane or microcontinent that may have collided with the northern Wyoming province along a generally SW-NE vector is difficult to specify. Evidence of >1.77-Ga crust in the western GFTZ and areas farther west, however, is quite abundant. For example, Leeman et al. (1985) reported Archean xenoliths from the margin of the Snake River Plain (Idaho), Lush et al. (1988) reported Archean rocks from the East Humboldt Range (Nevada), Kellogg et al. (2003) reported 2.4-Ga gneisses from the Beaverhead Mountains, and Mueller et al. (1996) reported 2.2–2.4-Ga xenocrystic zircons from the Tobacco Root batholith. In addition, the presence of 1.75-Ga crust beneath the Idaho batholith (Toth and Stacey 1992; Foster and Fanning 1997) that is at least in part juvenile (Mueller et al. 1995) is compatible with a scenario involving the subduction of at least some oceanic lithosphere in this time frame. Collectively, these observations suggest that the western part of the GFTZ may have experienced a distinct Paleoproterozoic episode of metamorphism and tectonism at 1.77 Ga that may not be directly related to the Wyoming-Hearne collision. If so, this younger event has important implications for the assembly of southern Laurentia.

Assembly of Southern Laurentia. Based on the number of terranes assembled to form Laurentia, the time required to assemble these terranes (∼150 m.yr.; Hoffman 1988), and the fact that Phanerozoic episodes of plate convergence commonly last for tens of millions of years, it seems likely that the assembly of Laurentia involved many collisions that overlapped considerably in time. Although temporal overlap of collisions between terranes does not in and of itself present a geodynamic problem, geodynamic problems can ensue if proposed collisional belts are contemporaneous and intersect at high angles (e.g., the Trans-Hudson orogen and the GFTZ or the Trans-Hudson orogen and the Cheyenne belt; Mueller et al. 2004; fig. 4).

In the case of the Trans-Hudson/Great Falls ter-

ranes, it has been proposed that geophysical trends of the GFTZ are truncated by trends of the Trans-Hudson orogen and that the GFTZ developed earlier than the Trans-Hudson orogen, perhaps in the Archean (e.g., Boerner et al. 1998; Gorman et al. 2002). The timing of magmatism and metamorphism recorded in the Little Belt Mountains of the GFTZ (~1.86 Ga; Dahl et al. 2000; Mueller et al. 2002), however, completely overlaps with the timing of magmatism and metamorphism in the Hearne-Superior part of the Trans-Hudson orogen (e.g., Hoffman 1988; Lucas et al. 1996; Chiarenzelli et al. 1998; Machado et al. 1999; Mueller et al. 2002). It seems more likely, therefore, that the GFTZ is, at least in part, the temporal equivalent of the Trans-Hudson orogen. If so, this means that simultaneous (~1.8–1.9 Ga) collisions were ongoing between (1) Wyoming-Hearne/Medicine Hat, (2) Superior-Hearne, and (3) Wyoming-Superior (Mueller et al. 2002, 2004).

Collectively, these juxtapositions present certain geodynamic and reconstruction conflicts that are difficult to accommodate with simple orthogonal convergence along recognized boundaries of the Wyoming province (e.g., Mueller et al. 2002, 2004*a* and fig. 4 therein). Our preferred model involves generally SW-NE convergence of all three cratons at ~1.8–1.9 Ga. In this model subduction-related 1.86-Ga magmatism in the Little Belt Mountains and the seismic evidence in support of a relic, north-dipping slab beneath the southern Medicine Hat block and Hearne province (Gorman et al. 2002) are accounted for by interblock convergence between the Hearne, Medicine Hat, and Wyoming blocks as they approached the Superior province. One possible configuration that would allow simultaneous, interblock convergence is depicted in figure 5, which shows en echelon arrangement of the Hearne, Medicine Hat, and Wyoming terranes approaching the Superior province from the southwest. In this configuration, initial collision of the Hearne and Superior in conjunction with continuing northeasterly motion of the Wyoming-bearing plate would lead to interplate convergence of the Wyoming and Medicine Hat blocks along what would become the GFTZ and of the Medicine Hat and Hearne blocks along what would become the Vulcan structure. The ultimate configuration of these blocks involved a component of lateral or strike-slip motion as these blocks arrived at their final positions (e.g., Dahl et al. 1999). This transform motion may have affected large regions of crust and at least partly explains the extensive regions of ~1.7-Ga K-Ar and Ar-Ar data from the northern GFTZ and the Vulcan structure (e.g., Bur-

wash et al. 1962; Sims 1995; Dahl et al. 1999; Mueller et al. 2002). Similar proposals for initial convergence followed by transformation into a strike-slip boundary have been made for other portions of the Trans-Hudson orogen as well (e.g., Reindeer zone; White et al. 1999)

Subsequent accretion primarily involved Paleoproterozoic terranes and appears to have begun at about 1.78 Ga and to have lasted until at least 1.71 Ga (fig. 5*B*). The best documented of these collisions is that proposed between the Wyoming and Colorado provinces along the Cheyenne belt. This belt extends along the southern margin of the Wyoming craton and has been proposed to be a consequence of juxtaposition of various Paleoproterozoic arcs against the Archean Wyoming craton (e.g., Karlstrom and Houston 1984; Chamberlain 1998; Karlstrom et al. 2001). Convergence vectors along this margin are difficult to define but appear to involve a significant N-S component (e.g., Dubendorfer and Houston 1987; Tyson et al. 2002). Simultaneously, the northwestern Wyoming province was experiencing high-grade metamorphism and tectonism that was probably related to convergence along a generally SW-NE trend (e.g., Harms et al. 2004*b*). Geodynamically, accretion of material along both the southern and western margins at about 1.7–1.8 Ga could be accommodated by generally NE-SW convergence of two plates (one oceanic with arcs and the other an amalgamated continental plate containing the Wyoming craton). Orthogonal collision along these margins (i.e., southeast-directed on the northwest and northwest-directed on the southeast) is difficult to accommodate in light of the lack of evidence for subduction beneath the Wyoming craton (e.g., Mueller et al. 2004).

The inferred SW-NE convergence implies that the Wyoming-Superior part of the Trans-Hudson orogen extends south beneath the U.S. midcontinent region to its boundary with the generally younger Central Plains orogen near the present southern margin of the Wyoming craton (e.g., Hoffman 1988; Klasner and King 1990; Nelson et al. 1993; Sims 1995). This model does not preclude extension of Trans-Hudson-age rocks to the southwest beneath Colorado (Hill and Bickford 2001), but it would be most compatible with a back-arc setting for the bimodal volcanic rocks of central Colorado and northern New Mexico (e.g., Barker et al. 1976; Hill and Bickford 2001). The model also is compatible with proposals that the 1.97–1.85-Ga tectonothermal activity recorded in the Archean and Proterozoic rocks of the Black Hills could be attributed to the juxtaposition of the Wyoming and Superior cratons (Gosselin et al. 1988; Redden et
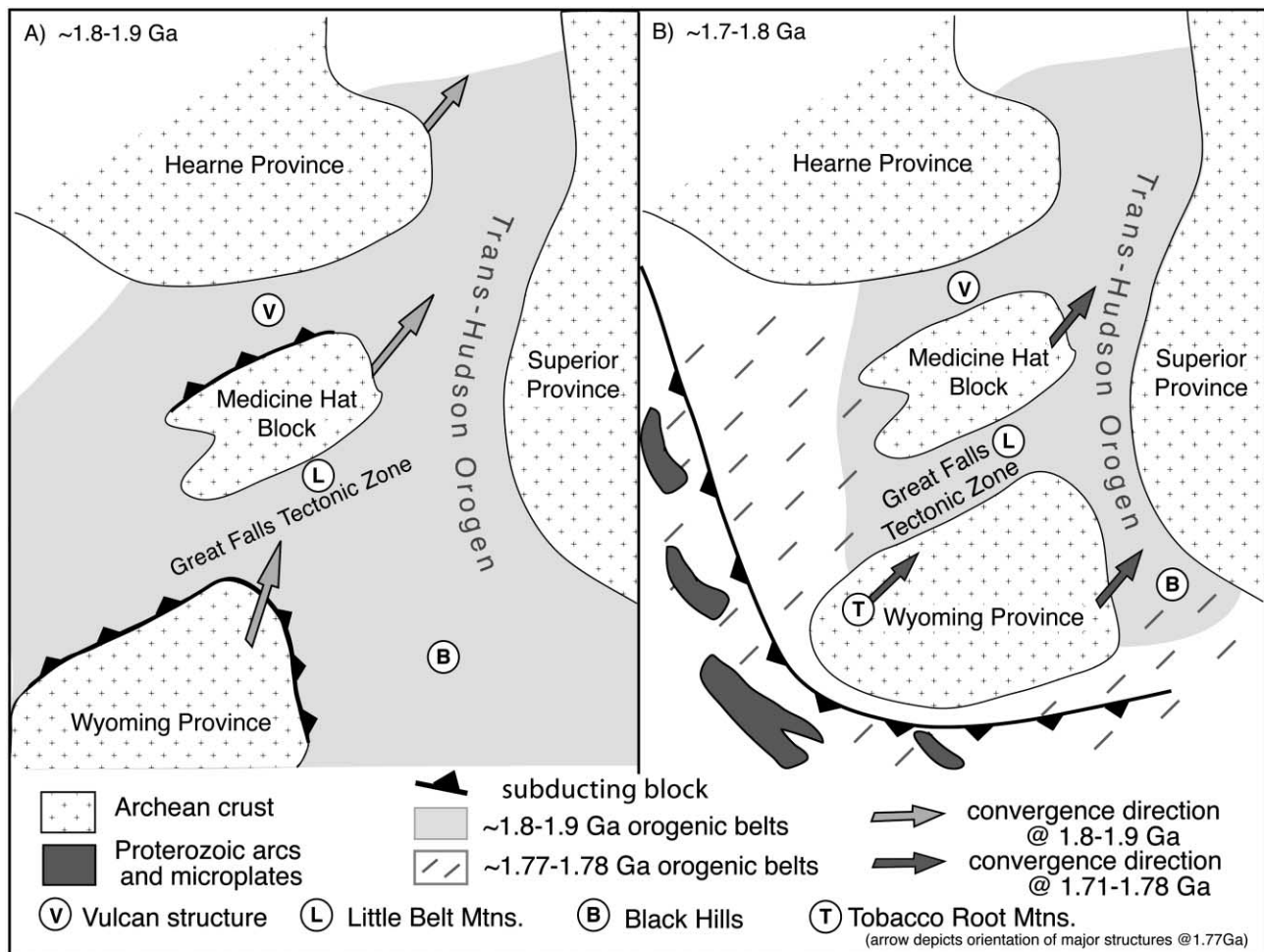
Figure 5. Possible configuration of major Archean and Paleoproterozoic crustal blocks now residing in southern Laurentia showing zones of Paleoproterozoic convergence in the frame of a fixed Superior province. *A*, Possible location and direction of motion for Archean crustal blocks at ~1.8–1.9 Ga with en echelon orientation resulting in initial docking of the Hearne, which prompts roughly simultaneous convergence with and between trailing Medicine Hat and Wyoming blocks. *B*, Possible configuration of Archean crust relative to accreting Paleoproterozoic crust in the interval ~1.7–1.8 Ga with continuing generally NE-directed motion. Convergence directions shown are schematic; real convergence directions are unlikely to be as consistent as those depicted.

al. 1990; Terry and Friberg 1990). This interpretation differs from that of Dahl et al. (1999), which proposes that the 1.76–1.71-Ga thermotectonism in the Black Hills resulted directly from Wyoming-Superior collision and was simultaneous with the Wyoming-Colorado collision (fig. 5). This model (Dahl et al. 1999) may present geodynamic difficulties, however, because it proposes that two active subduction zones intersect at essentially right angles (fig. 4).

We suggest, therefore, that the accretion of the Wyoming craton to Laurentia is best explained as a sequence of events that began with juxtaposition of Archean cratons and intervening Proterozoic magmatic terranes followed by accretion of predominantly Proterozoic arc terranes along the western and southern margins of the Wyoming province. The beginning stages of this assembly involved the largely simultaneous amalgamation of the Wyoming craton to other Archean cratons (Hearne and Superior) along the traditional trend of the Trans-Hudson orogen (e.g., Hoffman 1988) and other interplate convergent zones such as the GFTZ (e.g., O'Neill and Lopez 1985; Mueller et al. 2002; fig. 5). This period of accretion is distinguished by juxtaposition of Archean cratons only,

with magmatism primarily confined to intervening Paleoproterozoic arcs (e.g., Hoffman 1988; Dahl et al. 1999), as recognized in the Little Belt Mountains (Mueller et al. 2002) and throughout the Trans-Hudson orogen (e.g., Hoffman 1988). The second stage (~1.71–1.78 Ga) involved the accretion of Proterozoic arc terranes along the southeastern margin of the Wyoming craton (e.g., Cheyenne belt; Chamberlain 1998; Tyson et al. 2002), with concomitant collisional activity and reactivation of Archean rocks along the craton's margin (fig. 5). In the Tobacco Root Mountains, for example, convergent tectonism is characterized by granulite/amphibolite facies metamorphism, crustal melting, and overall reorientation of the structural fabric (Harms et al. 2004*b*). Provincewide, this stage is distinguished by multiple accretionary events that did not lead to the development of contemporaneous magmatism within the Wyoming province. The 1.71–1.76-Ga thermotectonism in the Black Hills (e.g., Dahl et al. 1999) and other parts of the older Trans-Hudson and Great Falls zones (e.g., Burwash et al. 1962) may reflect this later Proterozoic accretionary activity.

Summary

An extended period of ~SW to ~NE convergence with most, if not all, subduction directed away from the Wyoming craton may be all that is required to produce the continuum of Paleoproterozoic tectonism recorded along the margins of the Wyoming province between ~1.86 and ~1.71 Ga (fig. 5). The paucity of 1.71–1.86-Ga magmatic rocks within the Wyoming province suggests that the Wyoming craton's tectosphere resisted penetration by approaching oceanic lithosphere and that any mantle down-welling associated with these closely spaced convergent zones was limited to the margins of the Wyoming tectosphere. Consequently, the preservation of Archean subcontinental lithosphere beneath the Wyoming craton today (e.g., Vollmer et al. 1984) can be directly attributed to the strength and buoyancy of the tectosphere that developed during the Archean (e.g., Blum and Shen 2004; Mueller et al. 2004).

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